FACULTY OF TECHNOLOGY

Optimization of Sulfur Production in the Kittilä Mine via Deswik Software

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ABSTRACT

Optimization of Sulfur Production in the Kittilä Mine via Deswik Software

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The Kittilä Mine is an underground mine in northern Finland where sulfur content of the ore often restricts gold production. In order to optimize gold production, sulfur content of the ore fed to the mill must remain below a certain limit as to not overload the autoclave process.

An analytical look of the mining process was taken to ensure a solid understanding of the planning process for the mine's particular mining method. Various sulfur prediction methods were analyzed and using statistical analysis it was determined that the Primary Block Model grade estimates were the most effective grades to use in the remainder of the research. Deswik, the software in use for the mine's planning and production, was then examined and reviewed from a user's standpoint. Several aspects of Deswik were tested in attempts to create improved production plans regarding the sulfur limits or improved NPV. Throughout the trials, plans which included improved short term results delayed important development through the mine and disrupted steady production through the long term schedule. Other issues were found through trials, including the tendency of the optimization algorithms to take advantage of broken links throughout the task-progression network. The various methods and the corresponding results were compared and the advantages and disadvantages of the

Deswik system were assessed.

Keywords: Deswik, optimization, mine planning, software

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List of Abbreviations

CAPEX	Capital Expenditure
CIL	Carbon-In-Leach
LOM	Life of Mine
NPV	Net Present Value
OPEX	Operational Expenditure
PBM	Primary Block Model
SOT	Schedule Optimization Tool
TOC	Total Organic Carbon
USD	United States Dollar
XRF	X Ray Fluorescence

1 Introduction

1.1 Background

Agnico's Kittilä mine began underground operations and commercial production in 2009 and is now Europe's largest gold mine. The nearly vertical trend of ore is composed of over 100 relatively thin lenses, allowing for longhole open stoping with a delayed backfill; therefore production of ore using this mining method requires not only substantial underground development but also precise timing due to the several geotechnical aspects of the stope's production. Complicating things further, the majority of the ore is refractory and requires processing through an autoclave to alter the minerals to allow for the extraction of gold. In order to reach maximum efficiency, this additional process creates the need to balance the ore feed to the grinding circuit while also balancing the sulfur from the grinding and flotation circuit to the autoclave.

In late 2017, mineral reserves within the deposit were increased, leading to the decision of the mine's expansion. With the increased size of the mine, an increased production schedule has been introduced as well as several other projects to develop the infrastructure of the mine.

1.2 Problem

The mining method of longhole stoping with delayed backfill does not lend itself to rapid fire stope production. The process of producing a single stope requires diligent attention to the mining process in the surrounding area and although many different stopes may be chosen as the initiation point of a local mining sequence, this scheduled sequence becomes quite rigid once it begins. Not only is this mining process demanding in regards to the need for development, requiring significant infrastructure so that the many locations throughout the sequence can be accessed on time, but also technically strenuous in regards to the timing of the schedule; many geotechnical dependencies throughout the mining sequence involve the curing of backfill. Because of these aspects, it is very important to create the best schedule possible by selecting mining areas and sequences that will not only meet the production tonnage targets but gold and sulfur grade targets as well.

Diligent mine planning has allowed for the creation of a thorough and economic schedule. Certain bottlenecks involving sulfur grades drive mine planners to wonder if something can be improved in the production schedule. Although the Life of Mine schedule is already finely tuned, the network of mining tasks to be completed within the orebody is so massive that one can only assume that an optimization algorithm would be able to find an improved solution, a solution that results in a schedule which either further steadies the production of sulfur or bests the current Net Present Value of the current mine plan.

1.3 Target

The goal of the research is to optimize the sulfur grade and NPV of the current Life of Mine schedule. The target is to analyze these processes and give recommendations that improve the decisions made in the planning process, as well as to assess the capabilities and potential use of Deswik schedule optimization tools for the future. Both improving the mine plan by stabilizing the sulfur grade within production and increasing the NPV of the project would promote profitability of the mine's operations.

1.4 Limitations

Though computer optimization programs run powerful computations allowing for a large amount of scenarios to be assessed within a relatively short time frame, this process is not without imperfection. Most significantly, complete and perfect validation of each scenario, including the current LOM plan, can require an immense amount of scrutiny. This is due to the fact that these schedules all involve an enormous network of physical tasks, each with their own dependencies; therefore, because the task initiation depends on its completed dependencies, the dependency network must be examined and validated to the highest possible degree.

Other limitations are that the original mining tasks have not been changed and alterations to the mining activities and resources may affect results. Handling the LOM file with modified activities may create easier validation, however the total number of activities should increase drastically.

Additionally, all sulfur analysis is open to geological interpretation. Like all geologic and mining situations, the orebody at hand will never be fully predictable and requires knowledgeable professionals to assess risk and make educated decisions. In this way, sulfur data cannot be simply introduced to the financial model as it further requires human interaction before it has an effect on the production of gold. This is analogous to how it is impossible to determine the winner of a card game based solely on what cards were dealt to whom. Financial calculations throughout the rest of the thesis are based on a relatively simple model and should only be used to compare economics between variations of the models.

2 Background and Sulfur Analysis

2.1 Kittilä Mine Overview

2.1.1 Location and Conditions

The Kittilä Mine is located in Finnish Lapland, roughly 50 kilometers northeast from the town of Kittilä. The mine lies within the Arctic Circle where its climate is influenced by the Gulf Stream from Norway's coast. Winter temperatures may approach -40 degrees Celsius creating a need for a sheltered mill, and while snowfall is substantial, it is easily dealt with as mining operations continue underground regardless. Although relatively remote by European standards, Finland's thorough network of infrastructure provides ease of access through good roads, connection to a strong and stable power grid and a quality airport located in the town of Kittilä.

2.1.2 Mining method

Mining method in Kittilä mine is longhole open stoping with delayed backfill. Competent rock mass quality and a thin, near-vertical orebody describe a typical scenario for stoping, as other methods work significantly better with more massive ore bodies and deposits with a much more shallow dip. Stopes are scheduled to be mined in an alternating pattern so that two primary stopes must be mined and backfilled before the secondary space between them may be mined. This allows for mining to progress throughout a panel of stopes, following development, while allowing sufficient time for these stopes to be backfilled as well as allowing for the backfill to cure.

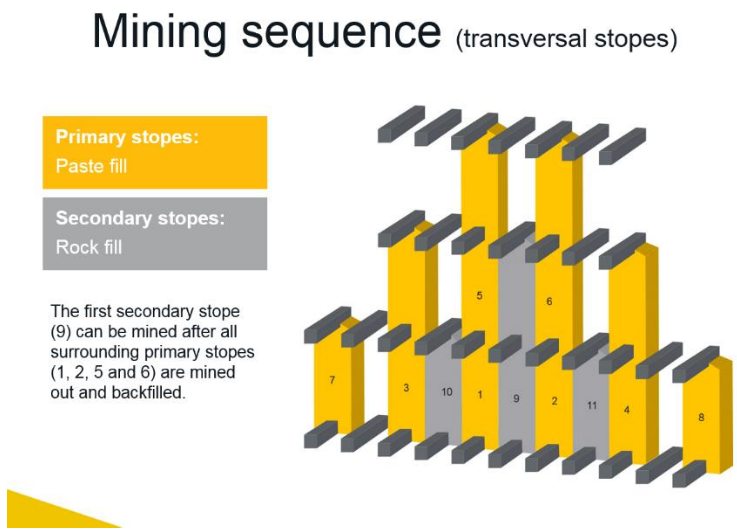


Figure 1: Standard progression of En Echelon stope mining scheme

Figure 1: Standard progression of *En Echelon* stope mining scheme, shows the typical schematic for the stoping sequence within a panel. Each stope's production relies not only on the geotechnical conditions of the laterally adjacent stopes of the x axis and the stopes above and below on the z axis seen in Figure 1, but the sequence can also be influenced when multiple lenses and stopes lie along the y axis from one another.

Some stopes allow for lateral progression only, without primary or secondary dependencies. These are typically thinner stopes and do not need independent drives to each stope. The main drift is driven through the bottom and top of the stope and the stopes are mines in a direct sequence, with often two adjacent stopes being produced and backfilled simultaneously.

2.1.3 Local stresses and Future Mining Method

Local primary stress in the Kittilä area runs in a pattern from north-west to south-east. This influences the mining method to progress from the easternmost lenses toward the western footwall. This allows for the backfilled stopes to yield stress and to divert remaining stresses around the adjacent panels.

However, as the mine continues deeper the need for a strict pyramid stope design plan, or the *en echelon* design seen in Figure 1, becomes greater. While the current production stopes are positioned between 80 and 625 meters underground, future panels deeper than this current range will begin to accumulate higher and higher vertical stresses. This *en echelon* design with a sharper vertical arrowhead pattern will allow for high vertical stresses to be properly diverted around the mining panel. Adjustments to the production schedule will likely be made as the risks created by high stresses on the orebody significantly increase with depth, diverting the mining schedule from ideal production based on financials to ideal production based on mine safety.

2.1.4 Mine Expansion Plan

Because of the increase in reserves throughout the mine due to recent exploration, the mine expansion is planned to increase production from the 1.5 MT mined in 2017, ramping up to 1.8 MT in 2018 and 2.0 MT in 2020. To keep hauling costs low, a shaft will be driven to the 900 level. The shaft will be the largest project during the expansion however the mine will receive many upgrades to the communication, task management, and other infrastructure systems.

2.2 Life of Mine Plan

The Life of Mine plan contains all foreseeable scheduled activities within the mine. By using the groups of stopes, or panels, and their given attributes, Deswik tools are used to help decide the best progression of development throughout the mine. After an initial schedule is given, it must be reexamined from other angles such as the tasks and resources required for the completion of each stage of development. After the schedule has been tailored to these requirements, the schedule can be broken down to yearly and monthly goals.

2.2.1 Panel Priority

At the foundation of the scheduling process, all panels and stopes are examined by gold grade and other feasibility factors and each panel given a priority value. Panels which contain high gold content are generally given higher priority and are therefore listed as such, i.e. highest priority panels are given a value of 1, while the lowest are given a value of 25 or less. Panels are given values to help organize the progression of the mining schedule, with multiple panels receiving the same priority value if deemed appropriate. After all panels have been assigned priority values they are then prepared for the scheduling algorithm.

2.2.2 Stope and Development Design and Attributes

After priorities are assigned, solids design work must first be completed before any further details may be added. This continued design consists of creating solids of stopes and development tunnels in order for necessary volumes to be reported. Tonnes of ore and meters of development are both key measures of mining progress in the mining model. Each figure is then given a set of attributes that describe its various aspects of creation. Some attributes are designated to describe the physical process of mining the area such as whether the stope is primary or secondary or what will be used as backfill material, while other attributes are given to be able to manage the data easily. These attributes include gold grade, mine level, panel, and many others.

2.2.3 Create and Link Tasks with Dependencies

When all stopes and development areas are given attributes, it is possible to break them into pieces in order to assign the task needed to complete them. Once each area is defined by the task needed for its completion, each task may be linked to another so that the logical order of development for the entire mine is able to be seen visually. When looking at the visual representation of this it is possible to see what sections of infrastructure must be developed just before the start of the mining of the stope, as well as which areas must be developed before those, and so on and so forth. This chain will lead all the way back to the current mining activities. By creating these dependencies and the arrows which indicate them, it is possible to visualize the path of development into the future areas of the mine.

While dependencies between development tasks are typically quite simple, dependencies between stopes become more complicated. A number of geotechnical limitations apply to each stope, and therefore the task of mining each particular stope is dependent on the timing of the production of surrounding stopes. These dependencies implement a form of geotechnical safety and order which reflect the stope mining strategy, the *En Echelon* scheme seen in Figure 1. After completion of the network, all dependencies shown in connection to a specific stope represent all rules that define when that given stope may go into production as well as which additional tasks are dependent upon the production status of the aforementioned stope. This creates a very large and complicated network within the mine and allows for various combinations of stope sequences to be assessed.

2.2.4 Adding resources

While the linked tasks make it easy to visualize how development will progress, it is still difficult to estimate the time required to complete this labor without additional information. In order to form a clear idea of the time required to reach certain goals within the mine it is necessary to inform the scheduling algorithm of the resources available to complete the given tasks. This allows for the program to recognize the amount of labor possible at any given time. For example, the program will know that if a given resource for Jumbo drills is three machines throughout the mine, there cannot possibly be four headings being drilled at once. Other resources incorporated in the model include the number of pieces of each machinery and the capacity to complete their job as well as the pace required to complete each extraneous task (i.e. three Jumbos, each capable of drilling 350 meters/month.) In the case of the Kittilä mine model tasks are organized into two groups, development which is handled by jumbos and production which is handled by loaders.

2.2.5 Creating Yearly and Monthly Goals

After the assignment of resources, the program is finally able to tailor the schedule into an achievable time frame. The schedule can now be broken into yearly and monthly goals. From here, the upcoming three months of planning will be under constant scrutiny, with alterations being made here and there as daily issues arise and resources shift in availability.

2.2.6 Level Reserves

Deswik Scheduler contains an optimization tool designed to balance both the mine’s tonnage production alongside the production of gold. By using the assigned priority values given according to the gold grade, the algorithm sifts through all panels, deciding that for each high priority panel that is focused on an accessible low priority panel must be developed simultaneously. All progression of the mine will be constrained by the linked dependencies within the network. This helps to create a feasible steady ore output month to month and in turn, a steady revenue year to year.

2.2.7 Short term planning and Shift planning

Beyond the yearly and monthly goals and schedule, short term planners must still keep a tight watch over the continued production throughout the mine. The process is further broken down to short term planning and shift planning.

2.2.7.1 Short Term Planning

The short term planning positions require constant attention to the progress of mining. As tasks are completed, the production forecast and development schedule must be updated regularly. Of course, a month by month schedule coming from a multiyear plan will not fit precisely into reality so it is the job of the short term planners to adjust the schedule and allocate resources based on a more precise estimate of what is available at the moment. With this procedure, the tasks have 24 hours of slack either direction of their start time assigned by the month to month schedule. If meeting the schedule becomes an issue, short term planners will continue to adjust each task's priorities until all resources are optimized and the schedule is met again. Meeting a tight schedule is not only taken care of by the short term planners but also by shift planners.

2.2.7.2 Shift Planning

Like the short term planning process, the goal of the shift planning process is to manage available resources to optimize production and keep on schedule. Shift planners are regularly working with shift foremen to discuss and manage daily tasks, employee's skill sets and short term goals. Meanwhile, cooperation with the control room is critical. The control room is the first receiver and recorder of all task initiation and completion data to the system. This information is used to keep detailed records of schedule progress for the rest of the mine to observe and react.

2.2.8 Shift Optimization

The Deswik Operational Tool has recently been implemented in the Kittilä Mine. This tool allows for current task updates by the mining crews via electronic tablets and eliminates the need for Excel spreadsheets for the tracking of tasks. Upkeep is still needed, however the increased ease of data transfer and task management is the most significant advantage when compared to the previous method.

2.3 Mine geology

2.3.1 Ore Body Characteristics

The Suurikuusikko trend from which the Kittilä mine produces ore is a relatively laminar orebody, striking north to south at a dip that ranges from -70 degrees to vertical at times. Ore produced from the orebody gets its value from refractory gold contained in the arsenopyrite and pyrite deposited throughout the trend. The orebody is often deemed as having a ‘pinch and swell’ formation which references the ore’s tendency to swell into some areas during its genesis, only to be abruptly pinched off, disappearing at one location and reappearing in another. In many locations throughout the trend, several lenses of potential ore can be noted. Their thickness ranges from as small as 3 meters, to as massive as 40 meters wide in some locations; most areas however, are 6-7 meters in thickness.

2.3.2 Geologists Role in Mine Planning

Geologists at the Kittilä mine play several roles in the process of mine planning. Within this process, the two primary tasks for geologists are to asses geology through the process of drilling programs which lead to the creation of secondary block models, as well as the management of ore stockpiles and creation of the mill feed recipe. Definition drilling programs are created level by level, customized to fit the planned development schedule of the upcoming stopes to be mined. After the core is drilled and logged, samples are sent to the lab and data used to create a definition block model of the area.

Geologists’ other critical task is to create a blending recipe to feed the mill. This is done through thorough record keeping of incoming and outgoing ore from each stockpile on a Last In, First Out basis. By keeping a close eye on the material balance of these piles, each of which organized by gold and sulfur grade, a recipe can be created to meet the needs of the required mill feed.

2.3.3 Stockpile Assessment

Some investigation of stockpile practices for grade control was done in order to assess the practicality of reorganizing the stockpile procedures used in the mine. The most significant constraint involved in the stockpiling of ore at the Kittilä mine is the minimal amount of time that ore from a stope spends above ground. As the stockpiles created during open pit mining diminish, the mill will be heavily dependent on ore coming directly from underground production to be used in the feed. Feeding the mill in this hand to mouth fashion will undoubtedly cause problems when stope grades are mispredicted and material is constantly fed to the mill before sample data from the stopes is available for planning uses.

2.4 Understanding Sulfur Content

Evaluating the source and viability of sulfur content estimation and prediction methods is crucial to understanding the limitations of creating a mine schedule based involving such predictions. It is important to make a note on the nature of geologic data based off of samples. Data interpreted on a geospatial basis is highly reliant on statistical analysis of spatial trends defined by the model of the orebody. This means that not only does the computation of geospatial grade predictions require parameters determined by a highly qualified person, but that further reduction of error within these grade predictions requires an increased number of samples and accurate data acquired from the samples, preferably in a cost and time effective manner.

2.5 Sulfur Grade Data Sources

2.5.1 Primary Block Model

During the creation of the primary block model, a variety of geologic data acquired from drilling samples are input to the database. This drilling program consists of an array of inclined and vertical drill holes, most of which are at 50 meter spacing to each other except where a closer spacing is otherwise decided on. This data gives the first and most accurate data for initial mine planning purposes. The block model algorithm estimates the percent sulfur (along with gold, TOCs and others) in the material spaced between drill holes; this is based on the most local data points to the point of estimation. This data is particularly valuable within the creation of the mine because of its long term availability prior to stope development as well as its reasonable reliability for planning uses due to the high accuracy of data recovered from samples during laboratory testing.

2.5.2 Definition Block Model

Secondary drill programs are regularly designed and put into action in order to take a closer look at the behavior of the ore from a level by level viewpoint. The core drilled in these programs is immediately taken to be logged by geologists. Core logging starts with estimations and other data collected via visual inspection, followed by samples being taken and sent to the lab for a quick XRF analysis. Samples are then sent for ELTRA analysis off site. XRF data is returned in a time period of 1-2 months from the drilling of the core but lacks significantly accurate results regarding sulfur estimation, although the data taken regarding the gold grade is accurate and used to further estimate the true value of the ore grade. Conversely, ELTRA analysis does create a significantly better estimation regarding sulfur content in the stope, however this data is regularly returned at an interval of roughly six months after drilling. Because of this delay in information, ELTRA analysis is eliminated from potential sources of data for planning uses.

2.5.3 SmartTags™ and Mucking Samples

Kittilä mine has a thorough procedure for the collection of samples while mucking. Every other loader bucket mucked from the stope has a sample taken from it, with the sample being labeled and tagged with a code that is shared by a Metso SmartTag™. The SmartTag™ is then placed in the loader bucket in order to keep track of the ore for grade control purposes. Currently the system reads Metso SmartTags™, the electronic sample RFID system, as they pass from the ore silo to the mill. This allows the operation to track which material has entered the processing circuit and estimate the grade of the mill input. Changes in the future may allow for more locations for the Smart tags to be registered as the material moves from underground to the mill.

Data from the mucking samples is considered to be the most valid representation of grade within the ore. This is because of the size, frequency, and analytical quality of the data. However, the data returns from lab no less than 48 hours after mucking, which means that prior to the return of the data, any material fed to the mill is assumed to have the grade of the stope represented in the definition block model. Thereby, if the lag were to be increased to a minimum of 48 hours with proper organization of stope material, grade control could be sufficiently improved upon. Regardless of the speed at which the lab is able to process results, grade control by SmartTag™ is susceptible to dilution as ore is mixed through the stockpiling process.

2.5.4 Mill Slurry Analysis

After the recipe of ore is fed to the mill it is then ground and homogenized through the SAG mill. Once entering the SAG mill, ore is unable to be traced back to its stope and any samples taken after this process must be seen as a representation of the recipe fed to the mill. The processing circuit has many points of data collection, some of which are more representative than others. Several XRF data points are in use, but as with the XRF data from the definition logging, sulfur data is only surficial and cannot be used as a proper representation of sulfur grade for research purposes. Through the mill, the best sample location for analysis of the grades of the recipe ore is the exit of the SAG mill. Here there is a sampling machine that takes a small sample of the slurry once an hour and deposits it to a container for drying. The sample is then collected and examined via ELTRA analysis on a 24 hour basis along with several other samples from different locations. This gives quality sulfur data in regards to the mill output, however this is a homogenized mixture of various stopes within the recipe. Other locations may be disregarded because of the processes prior to collection, these separate the material by size or mineral content, thereby disqualifying the sample from being a valid representation of the mill feed.

2.5.5 Understanding the Nature of Sulfur Grades and Predictions

It is important to address the nature of the sulfur content within the rock mass at the Kittilä Mine. Sulfur content is derived from the amount of sulfide minerals in the rock mass' composition, with the most common sulfides being pyrite, arsenopyrite and pyrrhotite. Sulfides such as these are often found in metal producing orebodies and are typically considered gangue or waste minerals. Conversely, common bedrock carries little to no sulfide content. Because bedrock has a very low sulfide content percentage, it is therefore key to recognize that the sulfur default value for waste material is zero percent, while the average PBM predicted sulfur value for ore material is 3.2%. Using this information, along with the data in Figure 2, the habits of the sulfur grade are able to be better understood. For example, it becomes clear that the likelihood of finding a stope with upwards of 5% sulfur is very unlikely yet still possible. Figure 2 also shows that since stopes are always a mixture of ore diluted with waste rock the sulfur data is naturally skewed to the right, this is because the probability is low for very high sulfur stopes to exist, while the probability is null for a stope to have less than zero percent sulfur.

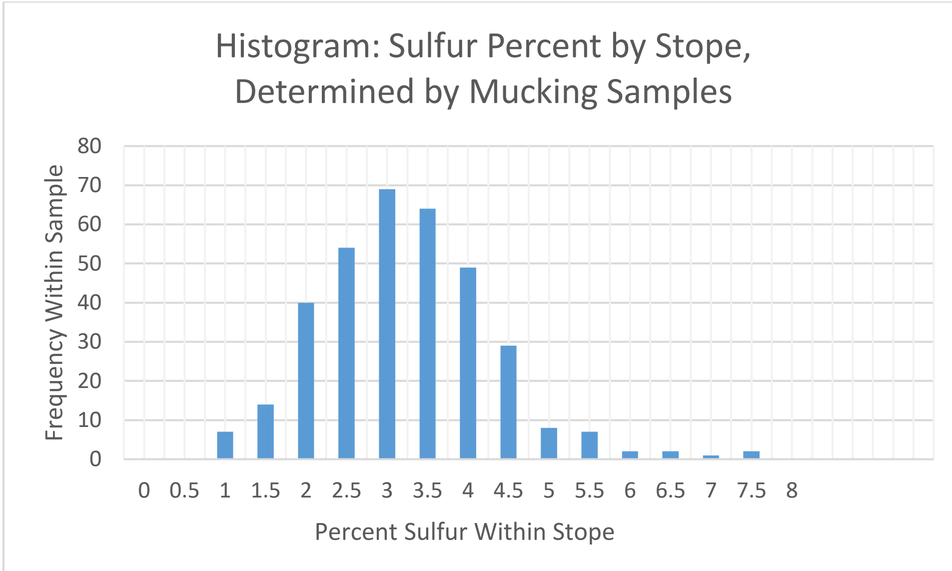


Figure 2: Histogram: Sulfur Percent by Stope, Determined by Mucking Samples

Sulfur data seen in Figure 2 and Table 1: Data Summary: Sulfur Percent by Stope Determined by Mucking Samples, as well as all data calculated in 2.6 Statistical Analysis: Agreement between Methods is calculated from Kittilä's Ore Reconciliation file. This file contains full reconciliation data for a sample of nearly 350 stopes mined in the years 2015-2018; reconciliation data includes various grades determined by block model, definition drilling and mucking samples, expected and calculated ore dilution, ore tonnage expected vs measured as well as other details regarding the mining of each stope.

Table 1: Data Summary: Sulfur Percent by Stope Determined by Mucking Samples

Data Summary: Sulfur Percent by Stope Determined by Mucking Samples	
Minimum	0.75
First Quartile	2.24

Median	2.91
Mean	3.002
Third Quartile	3.652
Maximum	7.49

The data in Table 1, when interpreted with the histogram in Figure 2, can be used to define how the sulfur grades are distributed. Section 2.7, Confidence in Sulfur Predictions, assesses how the errors in sulfur prediction relate to this distribution and what to expect during this prediction process.

2.6 Statistical Analysis: Agreement between Methods

After evaluating each source of data, three sources of sulfur estimation show to be the most valuable; these are the values from the Primary Block Model, the values collected via XRF during definition drill programs, and the data returned from the analysis of mucking samples. The first two are viable for planning purposes while the third is able to be used as a sort of standard or validation tool. While the mucking samples are not without error they return the most representative data available.

2.6.1 Method

Because examining the correlation of results from two or more methods of estimating the same data will undoubtedly give positive results, this analysis is not enough. The differences between datasets must be analyzed to check for agreement between the two results (Bland, 1986). Sample data was found from stopes mined from 2015 through 2017, this data includes grades estimated via all three methods mentioned previously. Without a source of data for validation, the difference between each grade estimation from the Primary Block Model data and the XRF data would be compared against the average of their grade estimate. Instead, because of the availability of the muck sample data, the difference in estimations from the PBM and muck sample data were compared against the difference in estimations of the XRF and muck sample data, thus creating two data sets with identical metrics. These two data sets were compared to assess the accuracy of each method.

2.6.2 Data

Data for the analysis originates from the ore reconciliation file, which records predicted and reported tonnage and grades from the Primary Block Model, definition drilling program and mucking samples taken during production. This spreadsheet is a useful tool for geologists and engineers as it logs nearly all of a stopes incorporated data, including the dates and duration of mining, planned and calculated dilution, number of mucking samples and so on. At the time of analysis, the sample consisted of over three hundred stopes mined between 2015 and 2018.

2.6.3 Analysis

Bland mentions the concept of 'limits of acceptability' in his paper discussing how to compare data taking methods; varying datasets require different levels of accuracy and acknowledging what qualifies data for acceptable use is important. This idea is strongly considered when replacing one method of taking data for another. Comparing the resulting data to the practicality of use is worthwhile in many ways, and sulfur grades should be examined in a similar fashion. The scale of the sulfur data involves monumental volumes of rock while thorough and highly accurate data collection can take ample time and money. Replacing one method with another or inserting an additional method of data collection is often cost prohibitive. In the mining context, predictive data collection should happen in one stage and its accuracy should correlate closely to the needs of the mine; unseen complications within the mine often arise and the previously taken data may not always able to meet the threshold of accuracy needed for perfecting day to day operations. In turn, the output of the calculations during the given process is only as precise as the input data; therefore a certain probability of error becomes inherent. This is often the case in mining and geological settings. With this, the data must be assessed and the best dataset must be determined so that all future calculations will be as accurate as possible.

By comparing the two data sets side by side, their differences become clearer and therefore a more reliable dataset can be established. Figure 3: Histogram for the Two Compared Datasets shows the frequency of varying levels of discrepancies between the measurements. Both are normally distributed samples, however the XRF data set has somewhat longer tails and a generally more erratic shape. This is the first evidence confirming that the XRF sulfur data is less reliable than the Block Model data.

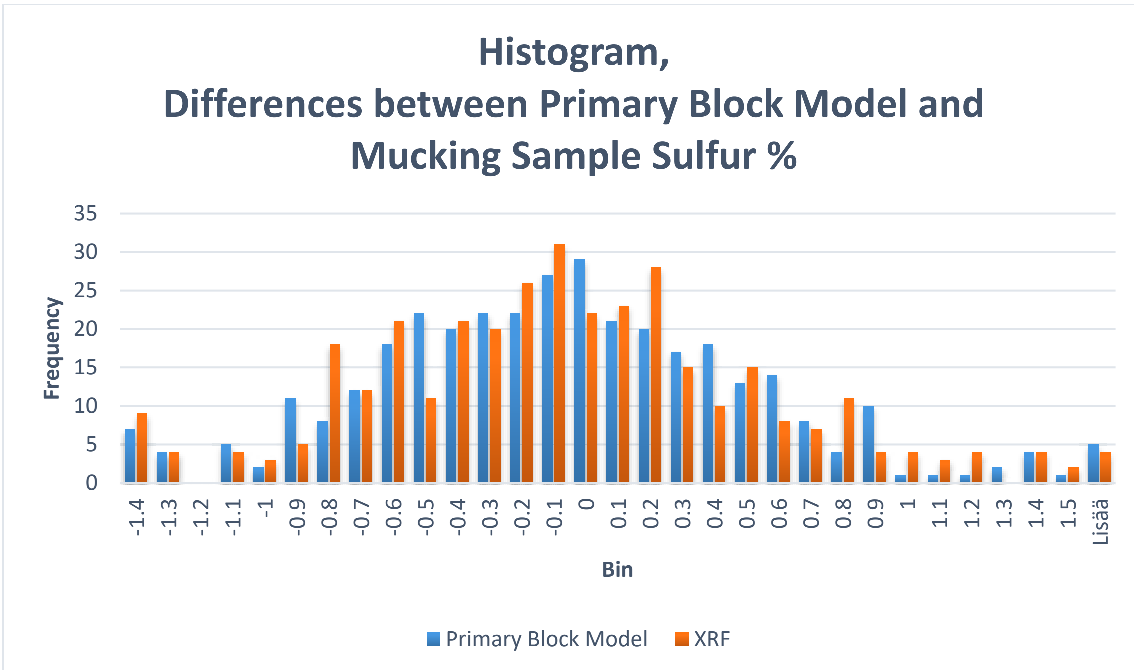


Figure 3: Histogram for the Two Compared Datasets

Another graphing tool used in comparing data sets when examining error can be seen in Figure 4: Comparing Error to Predicted Sulfur Values, where the x axis shows the determined sulfur value of the stope according to the mucking sample results. The y axis shows the difference in the values of the mucking sulfur against the previously predicted sulfur grade, whether it is via PBM or XRF. Here larger mispredictions are located further from the x axis, while correct predictions lie closer to the x axis. The figures show the yellow dotted lines as the average misprediction within the dataset and the solid lines above and below as the +/-2σ values (2 times the standard of deviation, the benchmark range which 95% of the dataset must rest between to be considered a normal distribution), these numerical values may be seen in the following Table 2, below. There is no clear difference between the compared methods in these graphs, although the general trend shows this; both PBM and XRF methods tend to be create somewhat conservative or centralized estimates meaning that their histograms would have shorter tails than those seen to the left and to the right of the normal distribution seen in Figure 2. This causes the general diagonal trend throughout the graphs. Mucking results plotted outside of the boundaries of the expected sulfur percent range (1.75-4.25%) are generally further from the x axis, showing that these have been largely mispredicted and the original prediction could be found by translating the points laterally towards the center of the graph by the same distance as their distance from the x axis. Essentially, the methods have a very difficult time predicting the more extreme cases of the sulfur grade. In the case of the block model, this is due to the fact that a stope will never be given a prediction that is of higher or lower percent sulfur than that of the most extreme samples in the database. When the local sample grades are projected into nearby geospatial volumes in this way, it is a very real possibility that the predicted stope may be within a pocket of material either entirely void of any sulfur content, a pocket of high sulfur material or anything in-between.

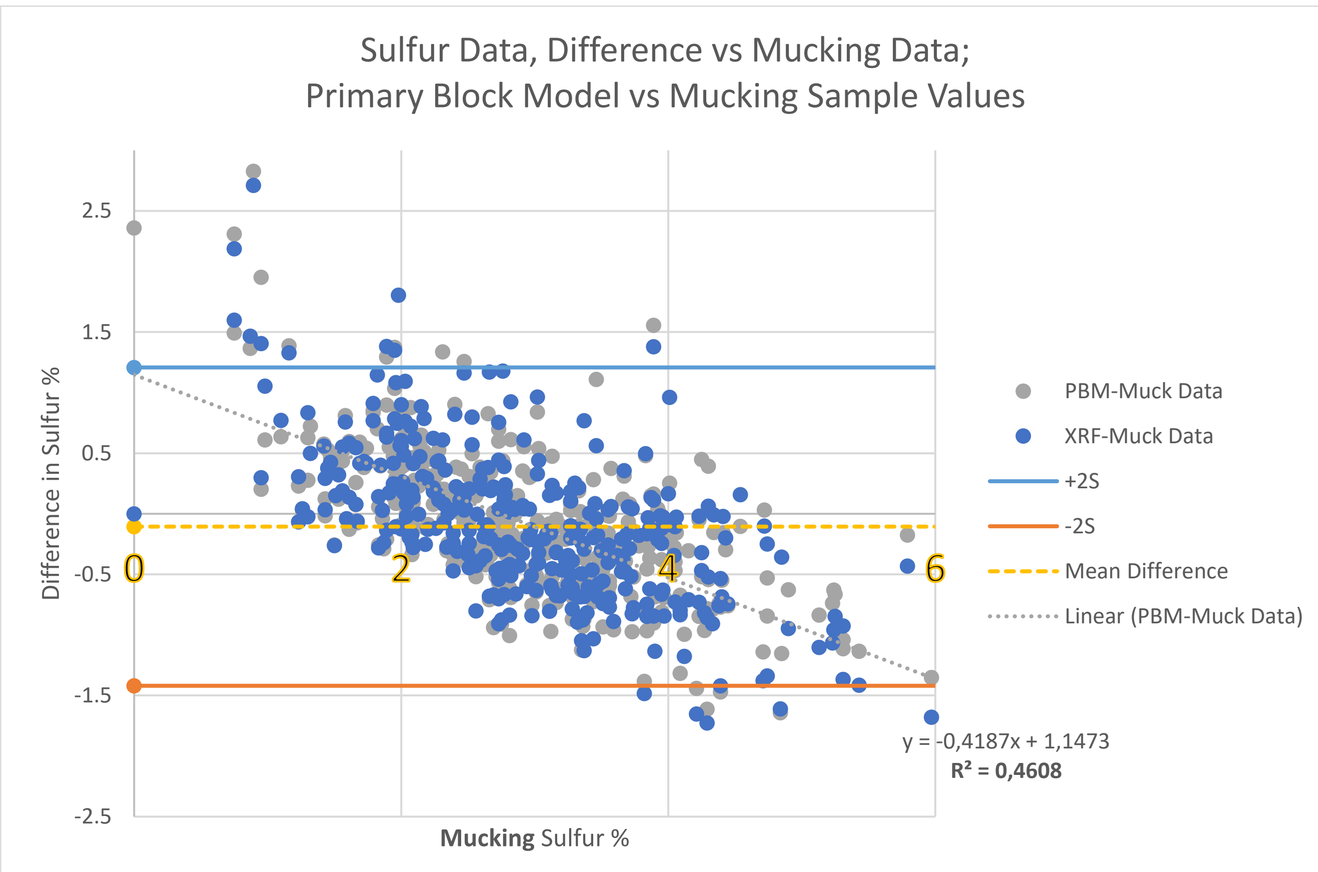


Figure 4: Comparing Error to Predicted Sulfur Values

Table 2: Mean Difference, Standard Deviation and 2Sigma for the Data Sets Given

	PBM-Muck	XRF-Muck
Mean difference	-0.11	-0.11
St.Dev. (σ)	0.67	0.68
+2σ	1.23	1.24
-2σ	-1.45	-1.47

Because of the concept that an ideal dataset for this application would be full of zeros, signifying that every prediction was completely accurate, it makes sense for the average error of each dataset to be very near to zero. This value, the average error of prediction, can be seen as the yellow lines in Figure 4: Comparing Error to Predicted Sulfur Values resting between 0.1 and 0.2 % Sulfur. Similarly, the standard of deviation for these datasets are relatively useless for this application as well. In order to find useful figures for this application it is best that the datasets are analyzed by their absolute values. In this way, the method which ultimately produces the least error will be clearly visible. Table 3: Mean and Standard Deviation for Gold and Sulfur grades in two Analytical Methods, was created to examine each method's success in grade prediction. Gold grade predictions were analyzed in the same way to validate the analysis as well as the use of the method. This is possible, following the logic that the XRF data is taken primarily for the purpose of reducing the prediction error in gold grade before production begins. Therefore the error data in the XRF column for gold predictions in Table 3: Mean and Standard Deviation for Gold and Sulfur grades in two Analytical Methods should be reduced in comparison to the values in the PBM column. This is the case and validates the model; the sulfur data shown in the table is nearly equivalent between the two methods with the block model showing a minute improvement in accuracy compared to the XRF data. The differences in accuracy between each method and the respective accuracy for these two elements give the best idea of each method's reliability and potential for application.

Table 3: Mean and Standard Deviation for Gold and Sulfur grades in two Analytical Methods

		PBM-Muck Difference (absolute)	XRF-Muck Difference (absolute)
S, %	Mean	0.45	0.46
	St.Dev.	0.46	0.47
Au, %	Mean	0.000078	0.000070
	St.Dev.	0.000074	0.000070

2.6.4 Conclusion

Based on the accuracy shown in the table above, both methods show a significant weakness in their ability to accurately predict a stope's sulfur grade. This case occurs often in mines where examination of a particular aspect increases in importance during the life of the mine and there is no immediate solution due to a lack of adequate preparation, showing again that mine planning is an all-encompassing and difficult process. Oppositely geologic mineral grades, especially in cases of higher grade low volume production where the orebody is not massive, are again often unreliable under micro examination, e.g. a stope by stope basis. In the given case, because of the minute accuracy advantage given by the primary block model data as well as the ubiquity of this data throughout the mine model, it is worthwhile to discard any plans of using the XRF sulfur predictions for any practical purposes within the study.

2.7 Confidence in Sulfur Predictions

While understanding the quality of each sulfur prediction is worthwhile, it is even more valuable to interpret the trends in the error within the prediction process. To do this, R- Statistics software was used to evaluate some basic statistical scenarios. Using the normal distribution of error between the PBM data and Muck Sample data, this dataset's mean and standard deviation were calculated and then input to a scenario which outputs the probability of the error exceeding a set of boundaries. This set of boundaries represents the error required for the grade estimated to break the 3.4% sulfur threshold.

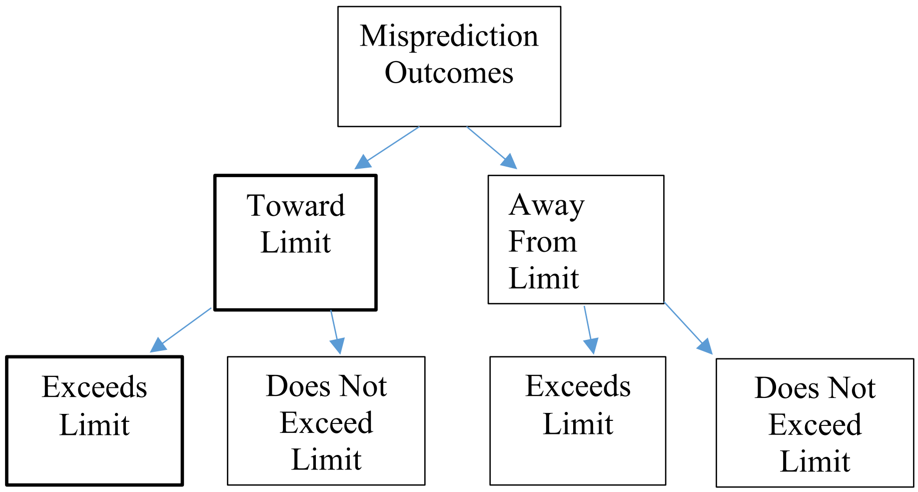


Figure 5: Outcome Tree for Sulfur Predictions

In order to calculate the probability that the sulfur grade will be under or over the 3.4% limit as predicted, it must be understood that there are only four outcomes in the situation (Figure 5.) The branches in Figure 5 show that the most critical outcome relies on two events in combination. The first set of branches show that the error of the misprediction must be in the direction of the threshold while the second set of branches introduce the possibility for the misprediction to either surpass the threshold or fall short. Upon understanding the principle of swinging toward the threshold, it is also worth noting that the misprediction of swinging 'toward' the threshold is qualified as overestimation or underestimation whether the original sulfur prediction is below or above the 3.4% limit, respectively.

Table 4: Under/Over Estimation Probability Data

Probability of Exceeding Threshold	Corresponding Range of Proximity to Threshold		Probability of Underestimation	Probability of Overestimation	Number of Data points
	Lower Limit	Upper Limit			

>90%	0	0.085	58%	42%	19
80-90%	0.085	0.1685	38%	63%	16
70-80%	0.1685	0.256	18%	82%	34
60-70%	0.256	0.35	38%	62%	29
50-60%	0.35	0.451	32%	68%	25
40-50%	0.451	0.563	45%	55%	31
30-40%	0.563	0.693	53%	47%	30
20-30%	0.693	0.853	41%	59%	34
10-20%	0.853	1.13	38%	63%	48
< 10%	1.13	2.5	43%	57%	82
		Mean	40%	60%	

Table 4: Under/Over Estimation Probability Data groups' data from the reconciliation file by the distance from the 3.4% Sulfur threshold and shows the respective fractions of these groups which were under or overestimated. The number of data points is included to show the sample size from which the data was created. Originally, this data was compiled into two separate tables, one including all data points which had a PBM sulfur prediction above the 3.4% threshold and another with all data points below this limit. The data regarding the Fraction Over / Under Estimated was no more highly correlated from one group to the next than the data shown in Table 4, and was therefore condensed into a more concise table. The most important trend seen in Table 4 is that ranges with larger sample sizes tend to stray less from the mean fractions than the ranges with smaller sample sizes, further validating that the mean fractions are representative for the entirety of the data. Ultimately these mean fractions are the best values to be used when estimating the probability of the first branch of outcomes in Figure 5; whether the prediction error swings toward or away from the 3.4% limit. The probability assigned to the event depends on whether the original PBM prediction rests below or above the sulfur threshold. For example, a value predicted to be over 3.4% requires an error which shows the value has been overestimated and is then assigned a probability of 40%, while a PBM under 3.4% will be assigned a value of 60% probability for an event of overestimation.

For the failure event of the misprediction across the threshold to occur, the two events in Figure 5 and their specific results must happen in combination. The probability of the two combined events is equal to the probability of the correct outcome of event one, multiplied by the probability of the correct outcome of event two. While the probabilities of event one, misprediction toward or away from the limit, is discussed above, the probabilities of event two are calculated much earlier in the section and define the data groupings seen in Table 4. This probability is a most accurately defined as an integral relating the area under both tails of the distribution curve of the PBM-Mucking error seen in Figure 3: Histogram for the Two Compared Datasets and the required size of error needed for the misprediction to cross the 3.4% threshold. To simplify, the data set was broken into twenty points, ten below the threshold, ranging from 5% to 95% probability, and ten above. These resulting probabilities, combined with the probabilities from the first event, give the resulting data seen in Figure 6: Probability that Error in Prediction Breaks Sulfur Threshold.

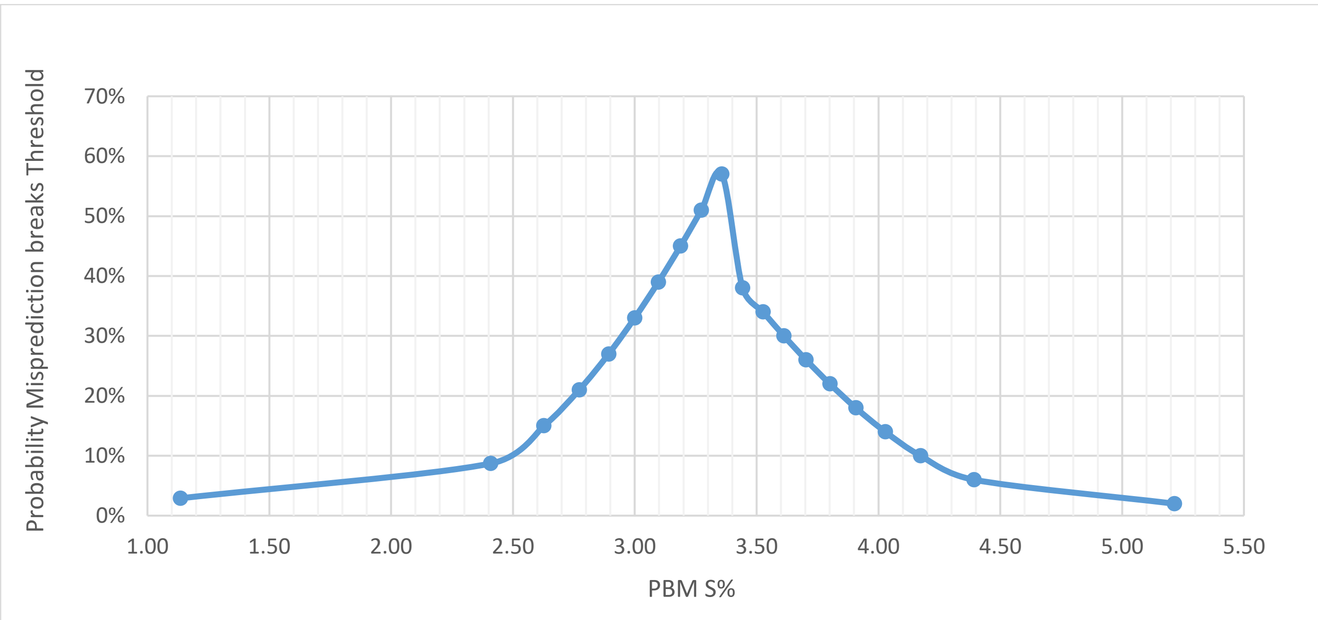


Figure 6: Probability that Error in Prediction Breaks Sulfur Threshold

The two most significant conclusions regarding the sulfur prediction process revolve around the data in Table 2: Mean Difference, Standard Deviation and 2Sigma for the Data Sets Given, and Figure 6 above. Table 2 contains the average and standard of deviation for the PBM-Muck sample prediction differences, while Figure 6 shows the probability of a stope's prediction to be mispredicted across the high/low sulfur boundary at 3.4% sulfur. The initial key is to understand that the average stope is underestimated by 0.11% sulfur while understanding the distribution of error of the PBM data seen in the first portion of Figure 3. Beyond this distribution data, the next most important data is understanding the likelihood of a serious misprediction across the 3.4% sulfur boundary. Figure 6 shows that the likelihood of a serious misprediction error increases with proximity to the threshold and also that the likelihood of underestimation is greater than the probability of overestimation at a 60/40 split. This difference in probability is what causes the asymmetry within Figure 6, if the likelihood of overestimation was the same as underestimation, the data would be symmetrical along the vertical line at the 3.4% sulfur. All of this data combined will aid geologists to make better decisions when preemptively categorizing ore to high and low sulfur ore and during the creation process of mill feed recipes.

3 Deswik CAD and Scheduler

3.1 What Is Deswik

Deswik is a mining specific, multi-faceted computer-aided design program which incorporates a mining schedule complete with tasks, resources and dependencies. The schedule may be manipulated independently or simultaneously of the graphic design using the interactive scheduling tool. Other add-on programs are available to be incorporated with Deswik CAD and Scheduler, including drill and blast design, Deswik Ops, a task management system to handle daily and short term operations, a stockpile and blending optimization tool Blend, a Schedule Optimization Tool, SOT, and others. Together these programs create one consolidated tool able to work through many needed mining engineering and operations tasks.

3.2 How Deswik Operates

The foundation of the Deswik suite is the CAD system and the scheduling program. Initially an ore deposit and geologic model are created through the program or transferred to the CAD system via Surpac™ or another XML source. As the processed is mentioned in the Life of Mine Plan sections, physical entities are created, be it either stopes, mining blocks in a pit, or other developments; attributes are then added to each entity. For best management of physical entities, all entities should have all defining physical attributes listed in its properties. This includes attributes such as any grade data, elevation or level, mining area, type of ore, or signifiers showing the required tasks to mine or develop the entity. This allows for easy examination later on by creating the ability to filter, group or sort the entities and tasks by any given set of attributes.

As the physical model develops, the physical entities are then broken into tasks and potentially into subtasks. At this point, the scheduling tool becomes relevant and dependencies are then assigned to each task. These dependencies range include basic requirements, e.g. Tunnel Segment A must be developed in order to reach and develop Tunnel Segment B, the segment directly behind A, to more complicated geospatial or attribute related requirements such as the need for a certain mining order between stopes. If a network is properly set up, this will allow for all physical segments of the mine to be assessed automatically within the scheduling tool.

After all tasks are linked appropriately, resources are added to the schedule by inputting the number of machines available and their capabilities. These capabilities will be matched to the requirements of a task to be completed. Using this principle and user inputs, the schedule program is able to assign equipment to each task in the mine's creation and develop a timeframe for the creation of the mine. It is worth noting that these tasks may be created as macro tasks such as 'mine this stope' with resources representing assumed capabilities of the team, or they may be broken down into several tasks requiring multiple pieces of equipment, e.g. 'drill', 'load' and 'muck this stope' requiring jumbo, ANFO loading team and loader resources.

The program then uses one of several tools to create a schedule. Currently there are three tools used to apply resources to tasks, Deswik Leveler, Blend and SOT; each with their own advantages and disadvantages.

3.3 Deswik Leveler

Deswik Resource Leveler applies multiple aspects of the mine production plan to the project tasks. Using a variety of rules and desired constraints as seen in Figure 7, the leveler organizes the schedule to fit the desired timeline and production rate of the mine. The Kittilä mine currently uses several rules to organize the Life of Mine production plan when using Deswik leveler. The first is 'Scheduling Priorities' which implements the panel priority values into the algorithm, guiding the schedule towards a sequence which is steady and economic. While the panel sequence is being organized, the Leveler is simultaneously using the 'Quantity Constraint' rule to choose stopes which meet the production tonnage guidelines for the schedule. When examining the Leveler's results, it may seem that the Quantity Constraint rule is influenced by the desired gold grade and sulfur grade within the stopes. This is not the case, and although these grades are more than acceptable for general production, these production plans can be attributed to the fine tuning of the panel priority values as well as additional tailoring of the schedule by altering constraint types and start dates of several task sequences. This feature, or lack thereof, of taking gold and sulfur grades into account is important to note as it is a significant difference between Deswik Leveler and Blend.

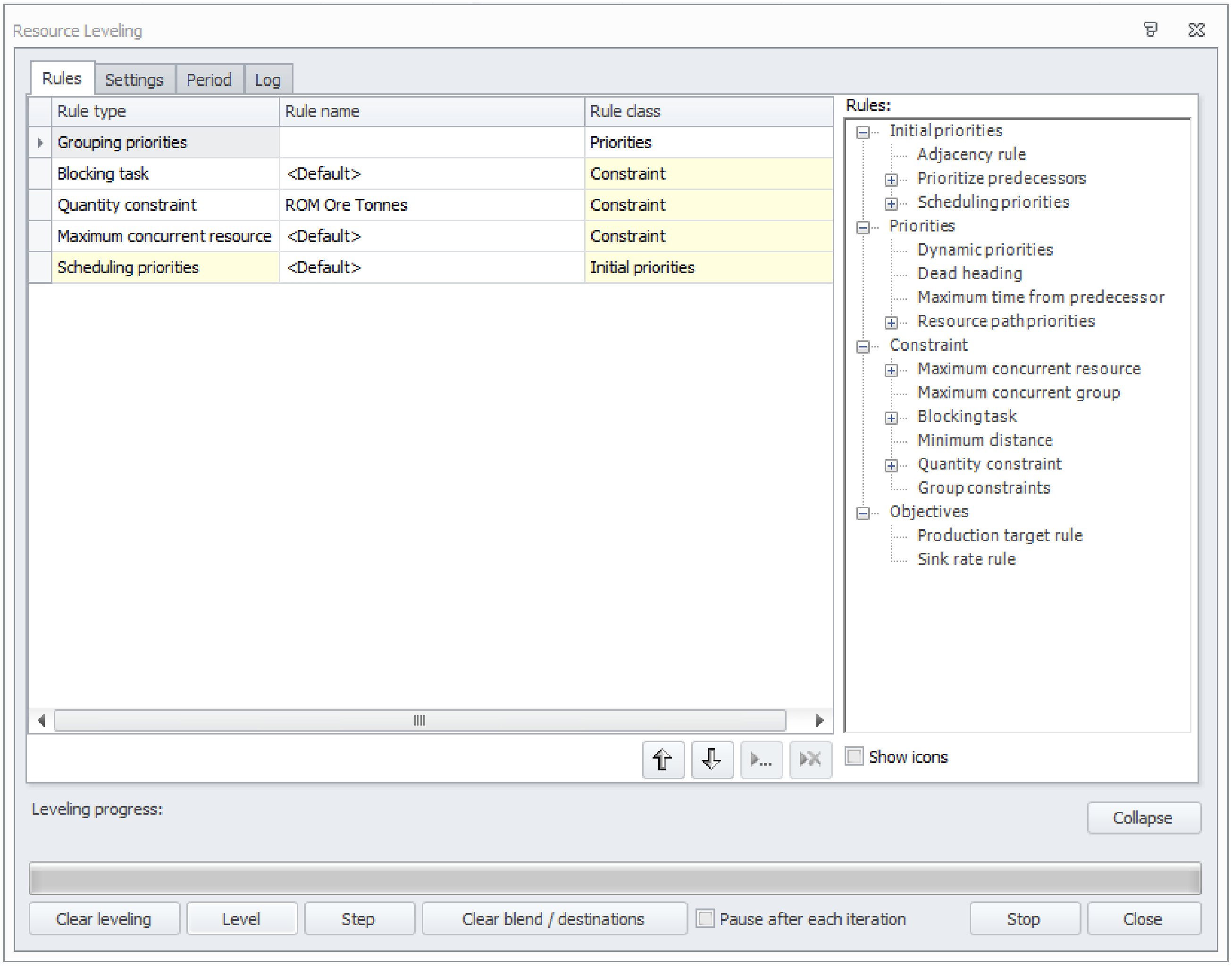


Figure 7: Deswik Leveler Rules Screen

Other rules within the Leveler allow for other priorities and constraints to be defined. These include how a resource is preferred to be utilized, with that kind of time frame a task may be completed and how resources may travel throughout the mine. Note that all priority options are soft constraints and may be overridden if another constraint takes priority. The ability to directly apply these preferences are what give the leveling tool a direct advantage over other scheduling tools. Figure 8: Deswik Leveler Settings Screen shows the settings features available within the tool.

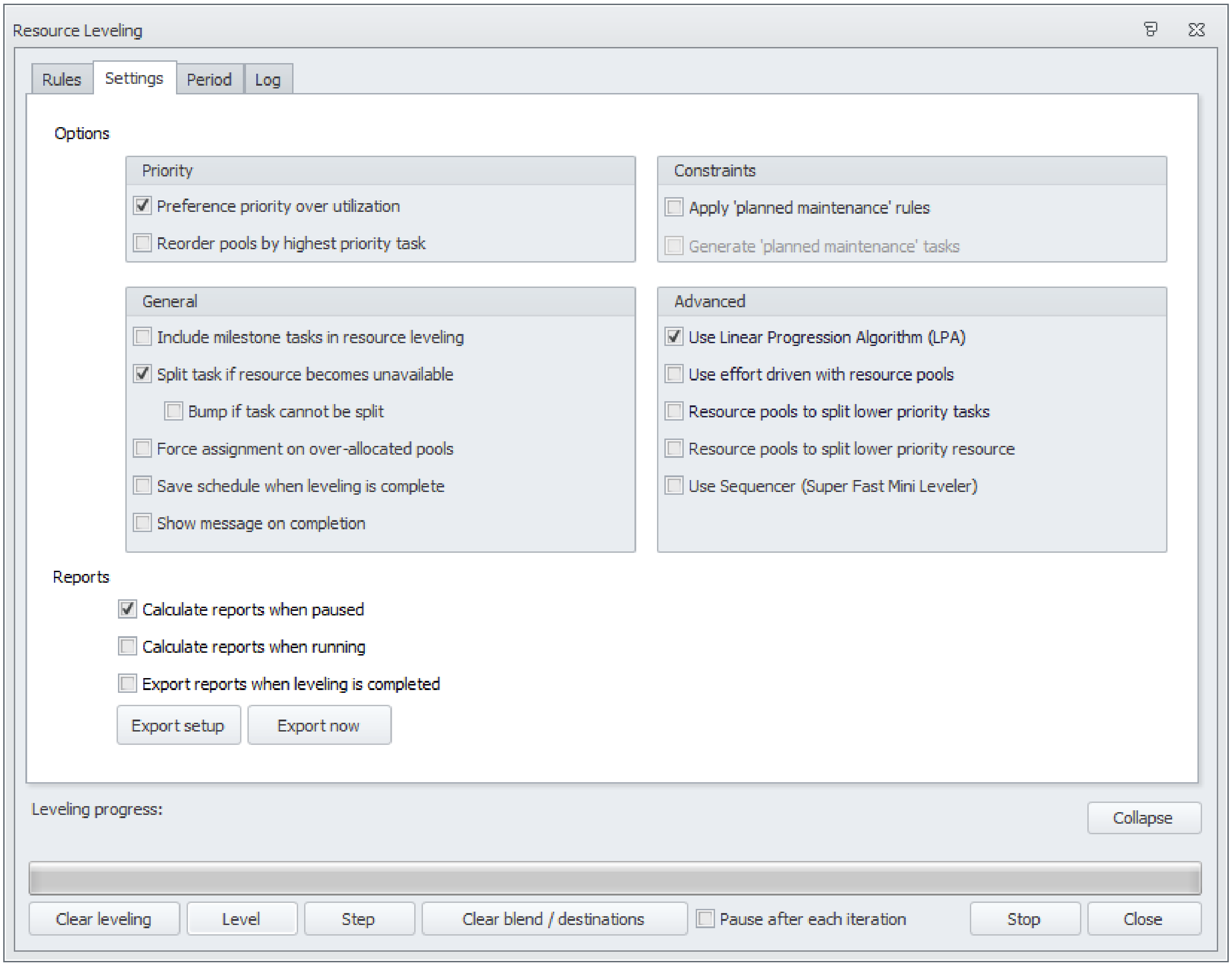


Figure 8: Deswik Leveler Settings Screen

3.4 Deswik Blend

While the resource leveler focuses on heavily on incorporating the mining activity model and how to best use each resource, the Blend tool instead defines the optimum production based on the site's capacity to produce and temporarily store the materials in production. Initially, the Blend tool begins with a Model Setup screen shown in Figure 9 below. The model should be assembled in the manner of the real life mine including the time periods for the tool to be implemented. The tool is designed so that all mine layouts are able to be modeled, including those that have multiple production sources, stockpiles, plants and products. Each point within the model is mapped accordingly and necessary data may be input to define the desired input and output of each node. Not only is each node mapped and defined, but materials traveling throughout the model must be defined as well. This can mean that waste, high or low grade ore, refined product and other materials included in the process may be given properties and associated to various areas of the model if it is deemed necessary.

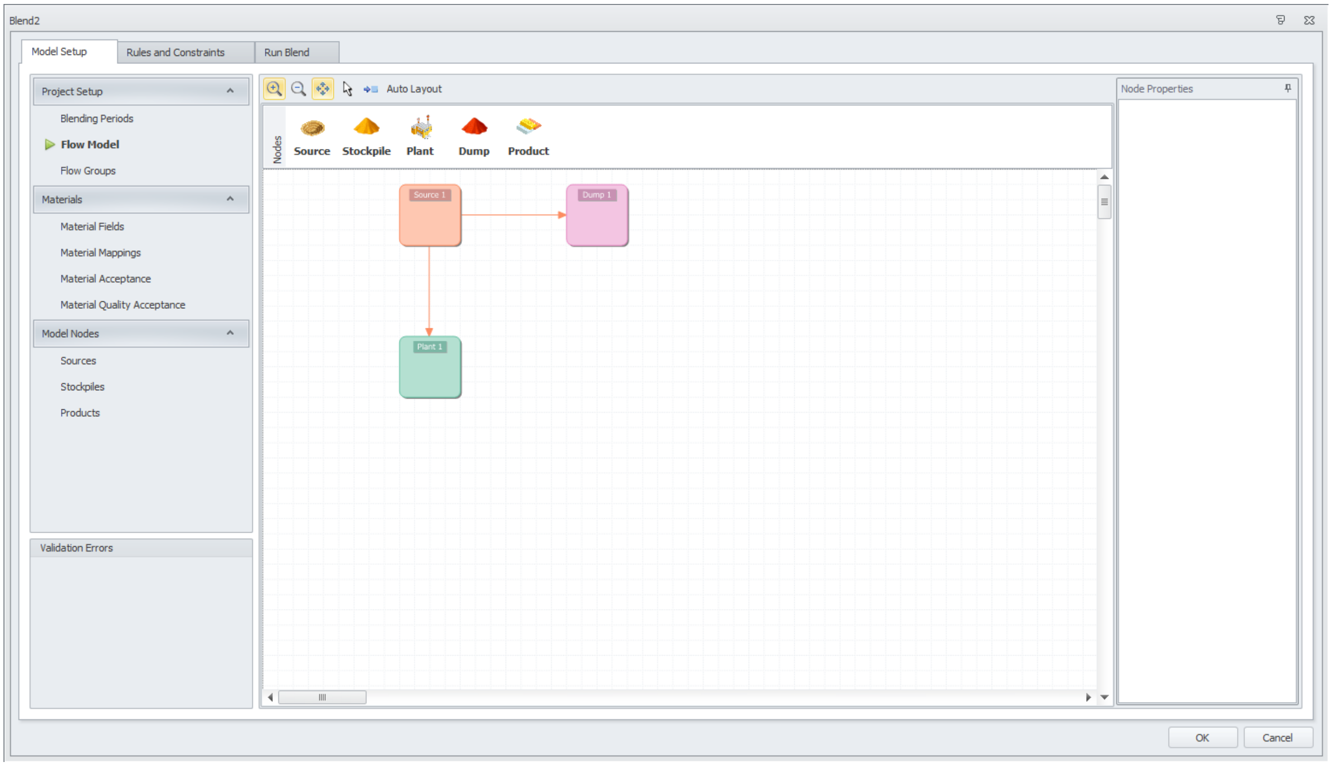


Figure 9: Deswik Blend Model Setup Screen

After the model has been mapped and materials defined, the constraints must be developed so that the Blend tool is able to distinguish what values are acceptable to output. Figure 10: Deswik Blend Rules and Constraints ScreenThe key constraints for the Kittilä Mine can be seen from Figure 10.This includes reaching as close to an exact production tonnage as possible, while keeping the gold grade above a minimum value and the sulfur below a maximum value. These values are constrained to be the average of a given time period, which in Figure 10 is three month periods. The length of each blending period greatly effects the results of the tool. Too long of a period and the results may be infeasible, allowing for uneven production in the schedule; too short of periods will create conflicts between resources and tasks, aiming for a production that is so even that it becomes unrealistic. During every blending period, each constraint is given a penalty value which allows the algorithm to assess its priority. After the constraints are given, many other aspects regarding input and output limitations to and from nodes are able to be altered. Finally, financial objectives are able to be integrated if suitable to the model.

In the final panel of Blend, run options are given. This gives options such as discounting the priority of constraints with time allowing for a stronger focus in the upcoming years, using driving resources within the schedule as compared to effort driven resources and whether the tool uses a faster more powerful solving algorithm to find the solution.

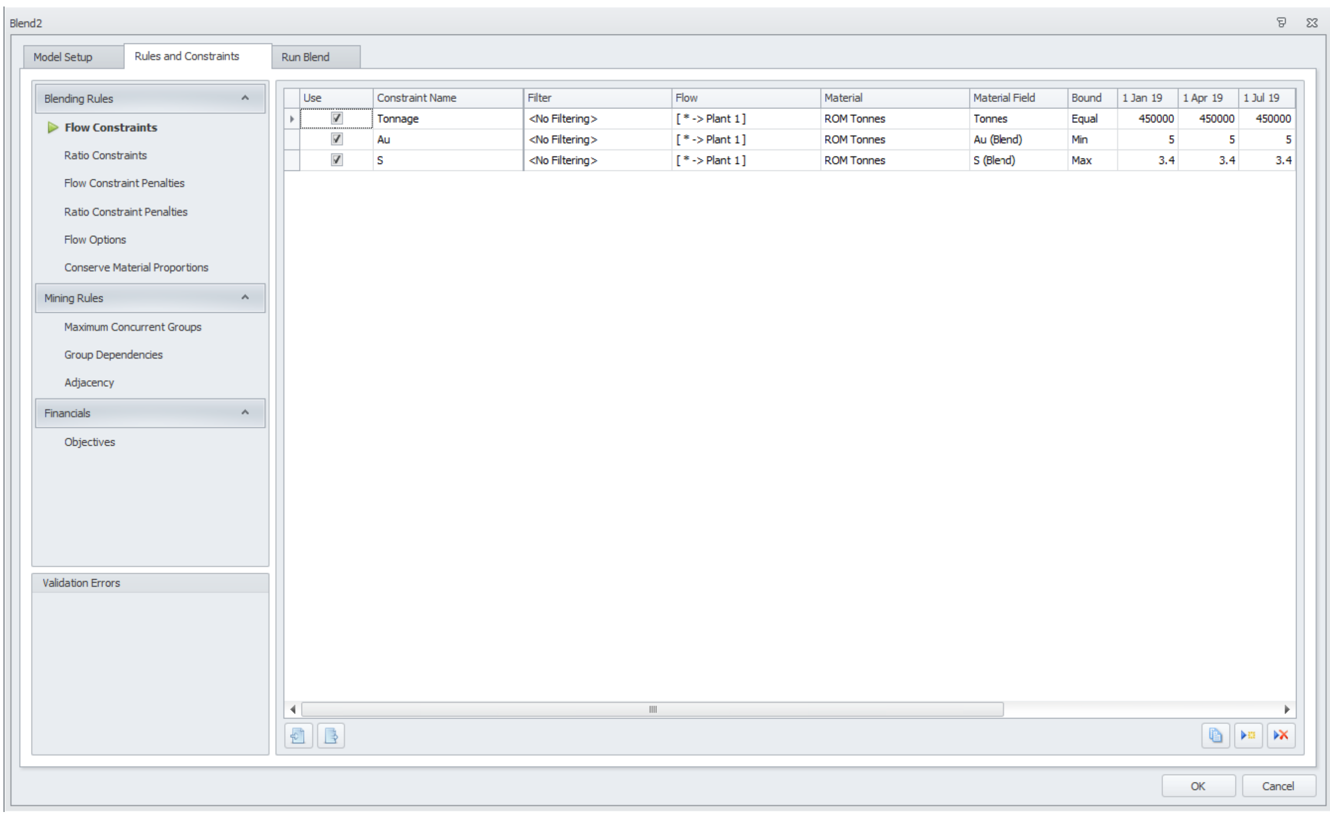


Figure 10: Deswik Blend Rules and Constraints Screen

The algorithm used within the tool is based on the principal that for every amount a constraint fails to be met during a blending period, a penalty is accounted for. In this way, the algorithm finds the best solution by minimizing penalties. This is able to be manipulated by assigning higher or lower penalty values where needed or by increasing or decreasing the constraint to influence the results in a given direction.

3.5 Deswik Schedule Optimization Tool

Schedule Optimization Tool or SOT is a scheduling tool designed to improve the NPV of the applied project. This is done by assigning costs to each task as accurately as possible so that each solid to be developed or mine within the mine has an appropriate cost estimate. The SOT algorithm them runs through a large number of permutations of the development of the mine, calculating the end NPV and comparing this to other permutations, as the tool creates an enormous tree structure of possible schedules.

Some critical aspects of creating valid results with SOT include the following principles: the costing for all types of tasks or areas of the mine must be representative, in the case of the Kittilä mine, this would be most simply broken into cost/meter of CAPEX development, OPEX development and cost/Tonne production. All schedules are permutated on a basis of the dependencies within the model therefore the entire dependency network within the model must be without holes. The optimization algorithm will find any pinhole within the network if it allows for an improved NPV. For example, this would include stopes preceding their needed development, allowing for profits to be made immediately while the costs are delayed.

A problem occurred during the implementation of SOT and due to an issue within third party software, SOT was not able to be properly investigated.

4 Process

Many variations of the LOM schedule were created throughout the research process. Because of the many steps taken to reach the end goal of finding suitable schedules, multiple controls were made to examine how intermediate changes to the schedule's settings affect the results within the schedule. A final template of the current LOM plan was created in order to introduce the new costing system as well as other potential settings that may have been used at later stages. This then becomes the root of the schedule tree, as all other models are stemming from this schedule and contain the same costing system for easily comparable NPVs.

A base schedule was created in order to form a schedule which removed any task constraints which require various stopes to be initiated at particular times. These constraints are not inherently negative to the LOM process, but instead are prohibitive when allowing the Blend tool to reform the schedule.

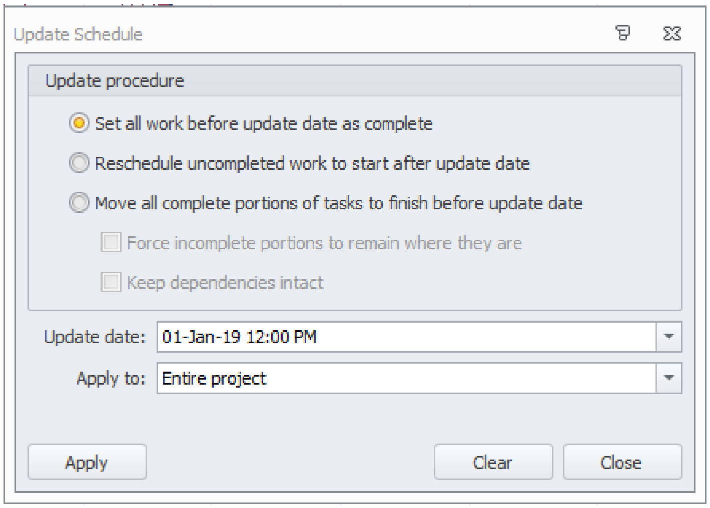
When using Blend without changing the settings from the base schedule, the development tasks remained set as “effort driven” tasks, and therefore were unconstrained by the resources. I.e., the production of development tasks would exceed resource limits when optimization pressure was applied to the schedule. To fix this, the development tasks were shifted from effort driven tasks to driving tasks, which are defined strictly by the resources allotted to the task over a unit of time. This led to the creation of the Driving Task Schedule. Due to the simplified nature of the tasks within the Kittilä mine, a workaround was found to emulate the pace and distribution of resources within the mine.

During the research process, a hypothesis formed that less dependencies through the network translates directly to more flexibility and therefore a higher NPV. This is often the case, however finding dependencies to remove without consequence can be tedious. An alteration to the Inter-Lens dependency rule was made so that more distant stopes were not reliant on one another.

Blend was used in an attempt to control the grade outputs within production for the Life of Mine. Issues arose due to the tool’s lack of planning foresight and so a variation of the use of this tool became the short term blend schedule. The technique behind the schedule required extracting a portion of the schedule to be mined in the near future, optimizing this short term schedule and integrating this schedule back into the full LOM plan.

4.1 Creating the Final Template and Base Schedules

In order to solidify and prepare the original LOM file, the schedule start was updated from an earlier date to January 1, 2019, freezing and completing all tasks happening before this date. This required changing the settings in both screens shown in Figure 11 below. Doing so eliminates any possibility of altering the tasks before the start date and clarifies the point at which the LOM is freed from the focus of short term planning.



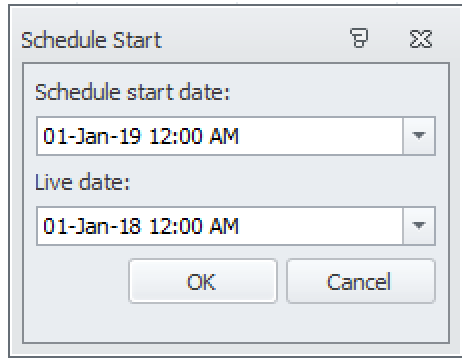


Figure 11: Update Schedule and Schedule Start Screens

Previously, no serious cost analysis was completed via Deswik. Revenue was calculated through gold recovery from ounces produced and the only cost was average €/tonne of ore produced. It is important to examine at how development and production must be balanced, therefore a current estimated cost of 80 € /tonne produced was split into 62 €/tonne for production and 2800 €/meter of development. All NPVs are calculated using a 10% Discount Rate.

A separate report template was created so that all critical details concerning the main aspects of the LOM plan could be accessed quickly and easily. All of the aforementioned changes were applied in order to simplify the creation of all future schedules.

This original LOM schedule incorporates several stopes through the use of a 'Must Start On' constraint. This constraint ignores all dependencies and initiates the start of the task on the given date. The constraint is used in specific areas which contain a dependency which may be ignored in order to begin mining. Stopes which this are applied to are looked over for validation purposes, however the constraint eliminates the flexibility for its timing and therefore it cannot be optimized. Changes were made to all tasks using these constraints to allow for blend to be run. The edited schedule was then saved as the Base schedule for further alterations for schedules.

4.2 Changing the Schedule to Driving Tasks

The goal of the procedure is to change the schedule from effort driven tasks to driving tasks. The original schedule uses the planned production along with the priorities in development and resources available in a given location to allow the creation of the development schedule. When this set of rules is used in Blend, the development becomes unconstrained and cannot be manipulated and reduced to a reasonable level for production. In order to control and slow the pace of development to realistic standards, a set of steps must be taken to change the views of the system on available resources.

First a new production field ‘Advanced Rate’ was created and its column added to the task reporting screen as seen in Figure 12. All filters and groupings were removed in order to view all tasks. All Task Rate data was transferred to the Advanced Rate column.

	ROM Ore Tonnes	Description	Advanced Rate	Task rate	Panel Priority	Driving property	Duration	Percentage Complete	Constraint type
12855	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12856	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12857	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12858	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12859	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12860	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12861	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12862	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12863	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12864	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.31mo	0.00	As Soon As Possible
12865	0	VINOTUNNELI 1	60.0	60.00m/mo	0	m	0.30mo	0.00	As Soon As Possible
12866	0	PERÄ	25.0	25.00m/mo	12	m	0.38mo	0.00	As Soon As Possible
12867	0	PERÄ	25.0	25.00m/mo	12	m	0.38mo	0.00	As Soon As Possible
12868	376	PERÄ	25.0	25.00m/mo	12	m	0.34mo	0.00	As Soon As Possible
12869	0	PERÄ	25.0	25.00m/mo	12	m	0.38mo	0.00	As Soon As Possible
12870	0	PERÄ	25.0	25.00m/mo	12	m	0.38mo	0.00	As Soon As Possible
12871	0	PERÄ	25.0	25.00m/mo	12	m	0.38mo	0.00	As Soon As Possible
12872	296	PERÄ	25.0	25.00m/mo	12	m	0.31mo	0.00	As Soon As Possible

Figure 12: Task Reporting Screen showing Advanced Rate and Task Rate Columns

A new Jumbo resource was added and all a standard settings applied, with the exception of changing the task from Effort Driven to Driving tasks, as well as using ‘[Advanced Rate]’ for the default resource rate. This rate is used instead of the most accurate value for a single jumbo because of the simplicity of the tasks assigned to each physical solid. For example, a development drift must be developed in the schedule by a jumbo, however in real life there are many more steps. The involvement of more processes than the jumbo alone means that the utilization of the jumbo throughout the development of the stope is much lower than the utilization of the jumbo in the Deswik process. Consequently, the jumbo will be utilized in other headings while these secondary tasks are under completion. The simplified idea causes problems in Deswik when using driving tasks because if a jumbo were to be assigned its full production meterage rate under these circumstances, there is no task to force it from completing its full meterage in a direct line. This leads to unrealistic development patterns within Deswik, therefore by altering the resource from a real world view of a low number of jumbos and a high development meterage for each to an alternate setting with low development meterage and a much higher number of jumbos, the program is able to emulate the natural progress of the mine's development.

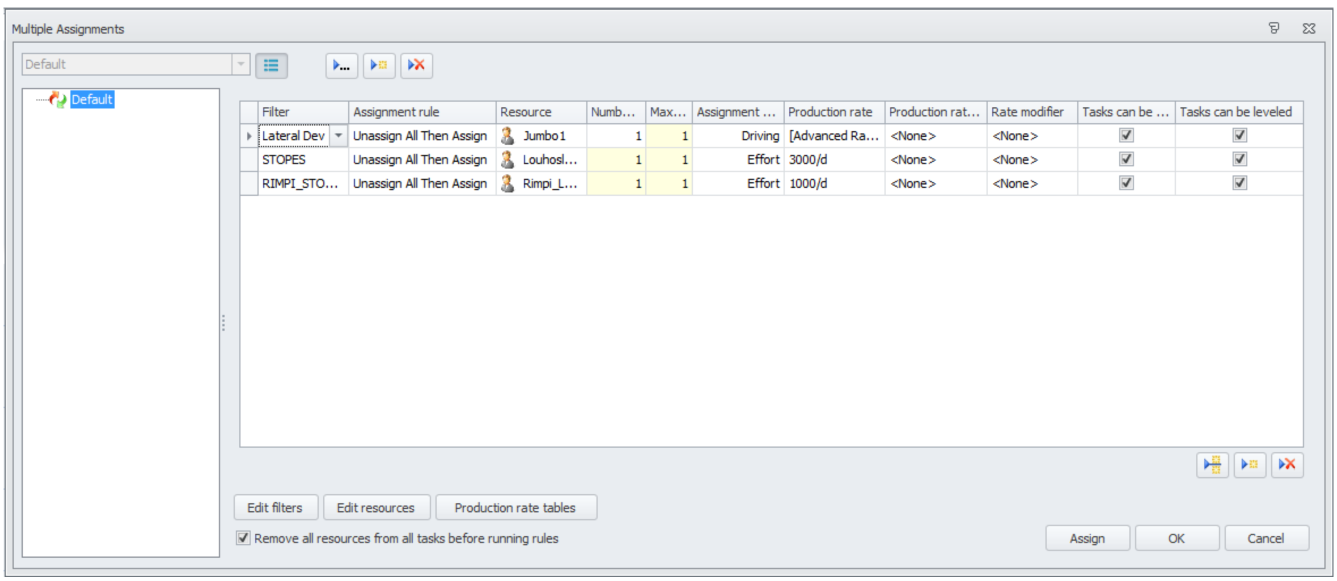


Figure 13: Multiple Assignments Screen

To enact the new jumbo resource settings, they must be applied to the appropriate tasks through the tool seen in Figure 13: Multiple Assignments Screen. A filter for all lateral development was applied so that the new driving resource would be directed to the applicable tasks. The new resource was assigned as Driving, while production resources remained on an Effort basis. '[Advanced Rate]' was again applied to the task rate as seen in Figure 13. It is good procedure to apply the assignment rule 'Unassign All Then Assign' to all assignments in order to keep the assignments organized.

Once all of the proper tasks are assigned, the resources may be finely tuned as seen in Figure 14. Beginning with a large number of resources, the leveler may be run and its results assessed. Resources may be reduced and time periods added for the purpose of adding or reducing resources within the given period. This will allow for the user to watch the results from each change in resources, and continually tuning the resources for the needs of the mine.

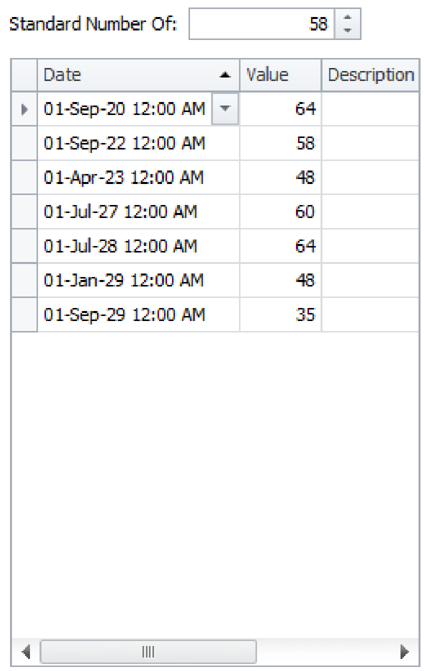


Figure 14: Finely tuned development resources for the Driving Task Schedule

4.3 Altering Inter-lens Dependencies

At a point in the research, all dependencies where analyzed by necessity. Originally it was thought that many could be eliminated, thereby simplifying the network and increasing the flexibility for optimization. Throughout the investigation, only one layer of dependencies showed a lack of criticality. This genre of dependencies connects one lens to another so that adjacent stopes from one lens to the next are not open simultaneously. The weakness seen in these dependencies is that each stope is only connected to the stopes directly orthogonal from itself within its respective lens. This means that while two stopes in different lenses and sharing the same position on the Z and Y plane are incapable of being mined simultaneously, one of these stopes and the stope directly adjacent to the other are absolutely capable of being open at the same time. Under these circumstances it would seem that the stress arc created by one opening could potentially influence the stresses on the stopes adjacent to the one orthogonal to the stope in production more than the stope directly orthogonal to the one in production. This would be due to the idea that the stope orthogonal to the one in production would rest completely in the shadow of the stresses dispersed by the one in the shadow. This led to the reassessment of the criticality of these dependencies. The current mining schemes for the Kittilä mine allow for this to happen, and therefore it may be possible to eliminate some of the standard orthogonal dependencies within the original layer.

Deswik CAD and the Interactive Scheduler, a tool which allows for the simultaneous viewing of physical entities and their corresponding tasks in Deswik Scheduler, must be used to view the dependency map for the Inter-Lens dependencies. By filtering the layers to view the only one which includes these dependencies the left portion of Figure 15 can be seen. This layer contains many attribute rule based dependencies and a portion of customized dependencies input by hand. To avoid disturbing these dependencies, all rule based dependencies were eliminated by altering the view to a downward angle such as in Figure 15 and deleting all perfectly horizontal lines in the frame. All other dependency lines do not follow the attribute rule given to the layer, therefore must have been input by hand.

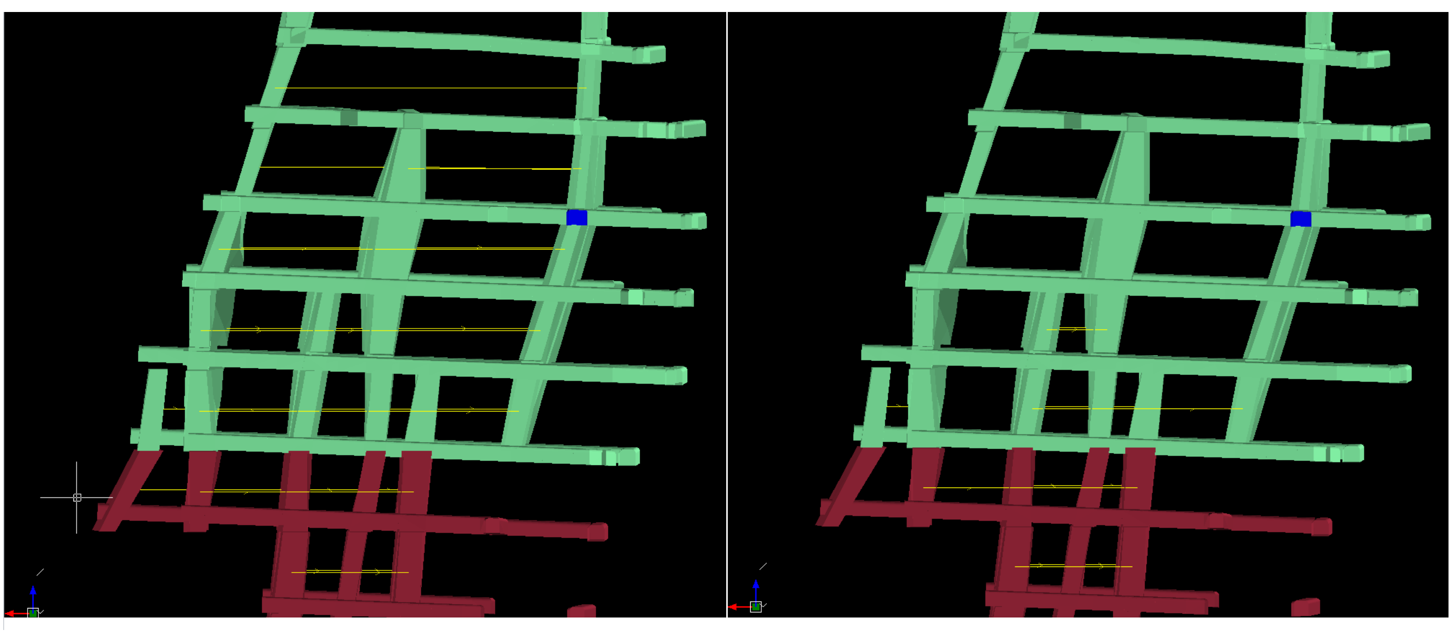


Figure 15: Partial Cross-Section of Suuri with Inter-Lens Dependencies in yellow, Before and After Alteration, Northward View

Once all automatically created dependencies were created, the rule for the creation of these dependencies was edited and all links were recreated according to the new rule. Originally the rule for this layer was for any stope sharing the sale level and position along the level in a separate lens to be connected regardless of the distance from one another. For this application the rule was changed so that any dependency whose centroids were further than 30 meters from one another was eliminated. The edit made to the rule can be seen in Figure 16: Altered Inter-Lens Dependency Attribute Rule.

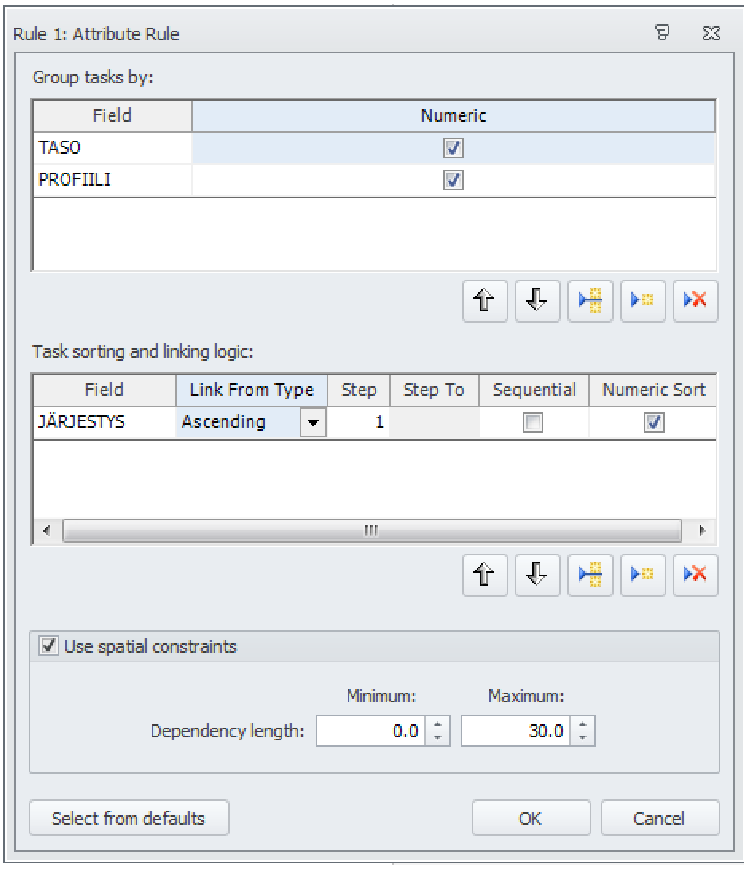


Figure 16: Altered Inter-Lens Dependency Attribute Rule

After the rule had been edited, it was run using the dependency creation tool and the physical map of dependencies checked. The new dependency map can be seen in the right hand portion of Figure 15. This new network was then leveled using the resource leveler and its resources adjusted.

4.4 Fully Blended Schedule

Blend Setup begins with determining the size and number of blending periods. A variation of the Base schedule, the blending period was allowed to run on a quarterly basis for 16 years.

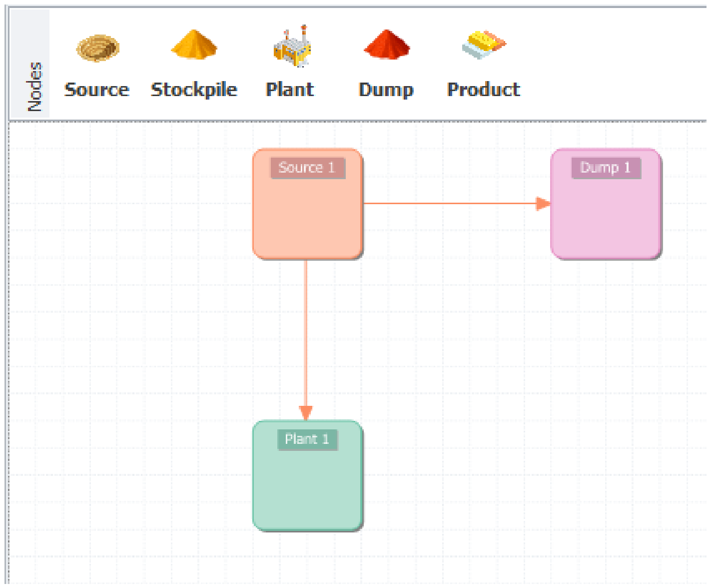


Figure 17: Blend Model Setup

Figure 17: Blend Model Setup shows the model setup screen and its capability to build a variety of models. The research uses the basic model that all waste will be sent to the dump, eliminating the possibility for the plant feed to be diluted with this material and that all ore will be transferred directly to the plant. No intermediate stockpile was used in the model because of short time period for the ore to rest between stockpiling and feeding. With such a short time period and relatively low volume in comparison to high production mines, the practicality of complicating the model with one or more stockpiles becomes null. Many minor steps are then taken to define material flows. Constraints are then entered as seen in Figure 18 below. The penalties for not meeting each constraint during a period may be changed as desired, however this did not prove critical for the given schedule. Final settings for the running the blend tool include making sure that 'Schedule-Blend Each Period' and 'Assign Driving Resources when Scheduling' are selected before using the tool.

Constraint Name	Material Field	Bound	1 Jan 19	1 Apr 19	1 Jul 19	1 Oct 19	1 Jan 20	1 Apr 20	1 Jul 20	1 Oct 20	1 Jan 21	1 Apr 21
Tonnage	Tonnes	Equal	450000	450000	450000	450000	450000	450000	450000	450000	500000	500000
Au	Au (Blend)	Min	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
S	S (Blend)	Max	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4

Figure 18: Blend Constraint Setup

4.5 Short Term Blend with Merge

The goal of the Short Term Merge schedule is to apply the blend optimization to the next several years of planned production while integrating the optimized schedule into the full LOM. To do this requires a series of complicated steps involving importing tasks and various constraint changes. Before beginning this sequence of steps, it was important to closely examine the distribution of development meters between the long term areas and development in the short term areas seen in Figure 19. This will give direction what amount of resource will be given to the short term project.

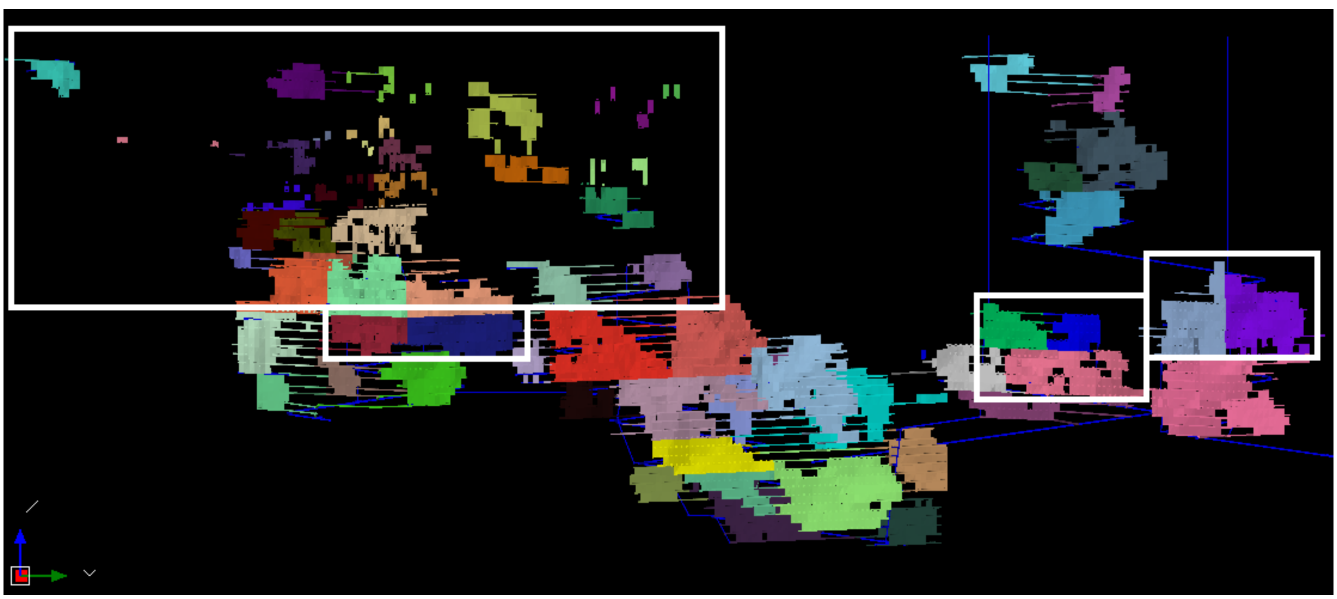


Figure 19: Selected Short Term Panels

A copy of the Base schedule was made and renamed as 'Short Term Schedule.' All tasks within panels which contain stopes to be mined within the years of 2019-2023 were isolated. These areas can be seen in Figure 19: Selected Short Term Panels. A significant portion of development was isolated along with these panels. All other tasks were deleted from the schedule. Using a Blending model and reduced resources allocated to the short term areas, the remaining tasks were blended on a quarterly basis for the years 2019-2022. This allows for the algorithm to properly optimize the mining areas, as it is able to decide on the best stopes available and any remaining tonnages will be pushed into the period after the blending cycle. A filter of 'Short Term Tasks' was then created for all tasks through this blending period of 2019-2022 and their constraints changed from 'As Soon As Possible' to 'Start No Earlier Than (date given by Blend)'

Another variation of the Base Schedule was created under the name of 'Short Term Merge' and opened in Deswik Interactive Scheduler. All stopes in production in the years 2019-2023 had their constraints changed to 'Start No Earlier than (01.01.2024).' This clears the production schedule for the new optimized schedule to be imported. Without this step, the imported schedule would overlap the existing one, making it difficult to separate the two when needed. In the Interactive Scheduler bar in Deswik CAD, 'Import Tasks' was selected, followed by the tasks in the 'Short Term Tasks' filter. All imported task data will then replace that of the same task name.

Next, the scheduler must be leveled and a filter set to view stopes only. These must be sorted by constraint type, then by start date in order to remove excess tonnage from the schedule by changing all stopes which are initiated by the constraint 'As Soon As Possible' within the years 2019-2022 to the constraint of 'Start No Earlier than (01.01.2023).' The schedule may then be releveled and its resources for development adjusted throughout further iterations.

5 Results and Analysis

5.1 Final Template and Base Schedules

The final template for the current LOM is the control when comparing all schedules. The NPV and other details in Table 5: Current LOM Schedule, Abbreviated Version, 2019-2024, show the planned values and expected NPV at a 10% Discount Rate. It is important to note that the cost estimates are lacking a significant amount of detail in comparison to the estimates used by Agnico for budgeting purposes. Therefore NPVs for all schedules should only be used as a tool to compare one schedule to another.

Table 5: Current LOM Schedule, Abbreviated Version, 2019-2024

---- Ore Summary ----	2019	2020	2021	2022	2023	2024
Total Ore Tonnes	1,809,641.18	1,805,961.78	2,007,003.05	2,004,233.87	1,998,998.23	2,001,404.35
Avg. Au Grade	4.50	4.48	4.52	4.80	4.50	4.47
Mined Ounces	262,076.78	260,345.76	291,961.66	309,321.05	289,443.55	287,589.03
Sulphur Grade	3.06	2.90	2.97	3.17	3.25	3.04
Total Development Metres Linear	20,336.99	20,195.67	19,024.49	16,352.58	16,759.20	17,128.16
Cash Flow	$ 65,130,555.90	$ 69,151,460.37	$ 87,954,361.08	$ 107,619,753.79	$ 87,618,273.56	$ 87,248,299.10
NPV	**$ 858,347,189.24**					

The Base Schedule and its abbreviated data is seen in Table 6. Because of the change to the schedule of altering all constraints to 'As Soon As Possible,' the selected stopes which are forced into the 2019 production year are released into the timing of the schedule where all of the tasks' dependencies are met. This can be seen in the shift of production tonnages from Table 5 to Table 6. The tonnages which are forced forwards into 2019 period in the Current LOM have all been verified by the mine planners at the Kittilä Mine. The tonnage shift made by the constraint change forces revenue into later time periods whose revenue is discounted more heavily than years earlier in the schedule. This is the cause in the difference between the two NPVs.

Table 6: Base LOM Schedule, Abbreviated Version, 2019-2024

---- Ore Summary ----	2019	2020	2021	2022	2023	2024
Total Ore Tonnes	1,659,956.02	1,842,185.16	2,086,246.88	1,995,643.43	2,072,345.33	2,001,404.35
Avg. Au Grade	4.41	4.52	4.56	4.78	4.53	4.47
Mined Ounces	235,133.75	267,851.53	305,705.71	306,392.48	301,787.66	287,589.03
Sulphur Grade	3.07	2.91	2.97	3.15	3.25	3.04
Total Development Metres Linear	20,443.96	20,084.27	19,145.29	16,352.58	16,759.20	17,128.16
Cash Flow	$ 51,206,501.80	$ 73,490,793.12	$ 94,504,917.20	$ 105,667,910.11	$ 93,542,874.03	$ 87,248,299.10
NPV	**$ 853,175,901.00**					

5.2 Schedule with Driving Tasks

After changes were made to alter the Base Schedule to the Driving Task schedule, one particularly significant shift was apparent. After the change from Effort driven tasks to Driving tasks, the resource leveler chose a different path than it had taken before. This was to be expected although the extent of which was unforeseen. The largest shifts when comparing Table 7 to the results given in the Base schedule, Table 6, are the low production in various years and the lower average gold grade. The only concern with this schedule is the high sulfur levels throughout 2021.

Ultimately the driving task schedule could prove to have a practical use for the Kittilä mine, although editing would be necessary to reposition the stopes which were held by alternative restraints in the Current LOM. Beyond this change, it would be conducive to the running of the Deswik program and the driving task schedule to create a minimum of one additional task type, e.g. Loading or Mucking, to allow for proper task rates in relation to the Drilling Driving task. This additional task could be edited to reflect various rates when applied to different physical spaces.

Table 7: LOM Schedule using Driving Tasks, Abbreviated Version, 2019 -2024

---- Ore Summary ----	2019	2020	2021	2022	2023	2024
Total Ore Tonnes	1,756,152.17	1,765,654.07	2,007,000.01	2,007,000.03	1,859,986.71	1,995,023.80
Avg. Au Grade	4.26	4.78	4.46	4.43	4.27	4.37
Mined Ounces	240,367.43	271,283.97	287,720.14	285,764.68	255,328.02	280,258.98
Sulphur Grade	3.05	3.05	3.55	3.04	2.99	3.13
Total Development Metres Linear	19,409.84	18,481.51	19,174.34	18,426.88	15,058.22	14,429.69
Cash Flow	$ 51,164,235.67	$ 84,598,659.77	$ 82,588,553.50	$ 82,408,374.36	$ 77,874,044.86	$ 86,968,396.57
NPV	**$ 842,715,345.43**					

5.3 Altering Inter-lens Dependencies

Throughout multiple drafts of effort driven or driving task schedules, the altered inter-lens dependency schedule consistently resulted in an NPV higher than that of the schedule it was branched from by two or three million USD. In this case Table 8: Driving Task LOM with Altered Inter-Lens Dependency Rule, Abbreviated Version, 2019-2024 shows the NPV increase and development decrease in comparison to the Driving Task schedule in Table 7. The hypothesis is that the reduction of dependencies allows for a more flexible schedule and therefore a reduced required development. One clear advantage of this type of alteration is its easy implementation. Dependencies can be assessed, eliminated and the schedule releveled. The disadvantage to these alterations are the time and effort required to assess the dependencies. Specialized personnel would be required as assessment would revolve around geotechnical and mine planning considerations. Another disadvantage of the technique is that the dependency type is far from ubiquitous.

Table 8: Driving Task LOM with Altered Inter-Lens Dependency Rule, Abbreviated Version, 2019-2024

---- Ore Summary ----	2019	2020	2021	2022	2023	2024
Total Ore Tonnes	1,814,763.82	1,797,000.00	2,007,000.00	2,007,000.00	1,991,061.43	1,851,397.68
Avg. Au Grade	4.36	4.61	4.55	4.41	4.31	4.35
Mined Ounces	254,309.78	266,615.08	293,298.50	284,324.54	276,173.77	258,779.09
Sulphur Grade	3.09	2.91	3.54	3.12	3.03	3.10
Total Development Metres Linear	16,395.47	18,070.33	19,813.96	18,587.82	16,435.72	16,390.99
Cash Flow	$ 64,000,529.28	$ 79,974,701.56	$ 86,530,456.65	$ 81,238,998.06	$ 84,686,646.33	$ 72,860,953.47
NPV	**$ 844,993,890.67**					

One aspect of Deswik Leveler was clearly seen in a recreation of this schedule. Initially, the dependency steps were recreated and ample resources assigned and leveled. This would allow for the scaling down of resources to find the lowest possible limit. During the reduction of resources, a lower limit was thought to be found, as the leveler tool began to show problems distributing resources. Typically the standard solution would be to increase the amount of resources at the time necessary and the next iteration through the leveler will be improved; a previous record of the schedules most economic resource schedule was documented during a prior version of the Schedule. The documented resources were significantly reduced compared to the schedule in the previous iteration, however the complication through the leveler was solved. Through some process, the resolution was to remove resources to be leveled. The key to understanding this is likely to understand how the Leveler fits many tasks and activities together. If asked to create a schedule with the best settings, it is possible, considering that all of these pieces fit together properly. If too many pieces are introduced to the schedule, the Leveler may make a decision which obstructs the path for the next tasks to continue to complete the schedule with fewer flaws. I.e., this problem likely revolves around alternate choices in the decision tree early on in the schedule. Unfortunately, due to the complex network created in the sublevel stoping with backfill method, the alternate schedule paths are tedious to create visually, difficult to analyze and strenuous to comprehend, as it requires an in depth knowledge of the mine and an incredible attention to minute detail throughout the task sequencing.

5.4 Fully Blended Schedule

A fully blended schedule was an anticipated goal throughout the research. Tasks were switched from Effort Driven to Driving for this purpose and many variations of the schedule were created. Results, however, were mixed. The algorithm within the Blend tool focuses immediately on satisfying the requirements of the blend periods, starting with the first period in the chronological sequence to the last. This method of satisfying constraints is impractical when advanced mine planning is needed. Because the algorithm does not take panel priority into account, the tool is unable to allocate resources strictly for the purpose of developing mining panels for future production. The full schedule shows a satisfactory gold and sulfur grade throughout the mine life, seen in Table 9: LOM Schedule with a Fully Blended Schedule, Abbreviated Version, 2019-2024, however because of the lack of resources dedicated to long term development, the development schedule is poorly planned. These improperly allocated resources continually develop nearby panels until all headings are completed and the only remaining developments in progress are drives which require extensive work. While these drives are under completion production dwindles along with development, this can be seen in years 2026-2029 in (table xx) in **Error! Reference source not found.**.

These issues, along with the lack of high grade material produced in the initial years of the mining plan are what cause the noticeable drop in the NPV within the schedule. In order to fix the development problems, the dependencies which bottleneck production must be identified and the constraints changed so that the task sequence will align the needed development with the proper timing. Considering the network of dependencies within the Kittilä mine, this is no small task.

Table 9: LOM Schedule with a Fully Blended Schedule, Abbreviated Version, 2019-2024

---- Ore Summary ----	2019	2020	2021	2022	2023	2024
Total Ore Tonnes	1,776,487.45	1,728,694.40	1,916,073.10	1,949,454.15	1,961,062.52	1,976,732.37
Avg. Au Grade	4.31	4.44	4.62	4.33	4.38	4.60
Mined Ounces	246,140.19	246,647.73	284,757.35	271,085.61	275,884.02	292,446.24
Sulphur Grade	2.95	3.19	3.12	3.14	2.98	3.12
Total Development Metres Linear	19151.95255	18600.53489	18177.91253	17621.0938	14365.27171	13746.49763
Cash Flow	$ 65,141,070.26	$ 69,508,197.16	$ 88,051,284.03	$ 73,936,629.69	$ 83,768,543.09	$ 100,106,594.86
NPV	**$ 764,474,829.55**					

Beyond the problems seen with the balance of resource allocation, other issues were seen in the process of visual validation of the schedule. During the viewing of the schedule animation, it became apparent that many bugs in the dependency network exist. Even with schedule validation completed in early stages of research, it was apparent that gaps in the network still existed. This could be seen by random nucleation sites for development and production stopes alike.

5.5 Short Term Blend with Merge

Although the Short Term Merge schedule was a successful workaround for the resource allocation problem that troubled the Fully Blended Schedule, it did not result in a satisfactory schedule. Blend was used to high grade the available panels while keeping production and sulfur goals satisfactory, as an attempt to force as much revenue as possible into the first three years of the schedule. The program succeeded in bringing revenue forward in the schedule however it did not successfully increase the overall revenue within the first three years. This is seen by comparing the revenues in Table 10: LOM Schedule with Short Term Blend, merged with Full LOM, Abbreviated Version, 2019-2024 and Table 6: Base LOM Schedule, Abbreviated Version, 2019-2024.

Table 10: LOM Schedule with Short Term Blend, merged with Full LOM, Abbreviated Version, 2019-2024

---- Ore Summary ----	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Total Ore Tonnes	1,785,795.56	1,797,000.00	2,007,000.00	2,007,000.00	2,004,346.40	2,007,000.00
Avg. Au Grade	4.82	4.39	4.34	4.37	4.45	4.48
Mined Ounces	277,007.05	253,358.36	279,987.39	282,158.34	286,703.79	288,877.59
Sulphur Grade	3.10	3.01	3.49	3.18	2.90	3.15
Total Development Metres Linear	20,879.06	18,979.35	19,027.40	19,061.52	16,939.71	16,113.44
Cash Flow	$ 78,724,904.60	$ 60,869,732.00	$ 71,307,594.19	$ 75,080,917.14	$ 96,367,120.71	$ 96,036,394.48
NPV	**$ 844,598,956.81**					

Upon validation, problems were found throughout the network. After experiencing and assessing this problem multiple times, it became clear that the dependency network is far from perfectly valid. Figure 20 shows several panels in the Rimpi area where the schedule shows the production of stopes without the drifts that they depend on. Figure 21: Drift- Stope Dependency map for Stopes without Development shows the same area without the physical solids. Note that some dependencies within the layer are missing. Under further investigation, some of these dependencies were only defined to one task, missing either the successor or the predecessor to the dependency, even though they are visually accurate. This particular error may be attributed to the enormous amount of work that occurs to the LOM file. Through complicated edits, it could be possible to shift or delete multiple dependencies by accident and often this mistake does not have a quick fix. The file is a compilation of work done through many stages and its size and the large amount of data that has been applied to the file makes its replication a burdensome task.

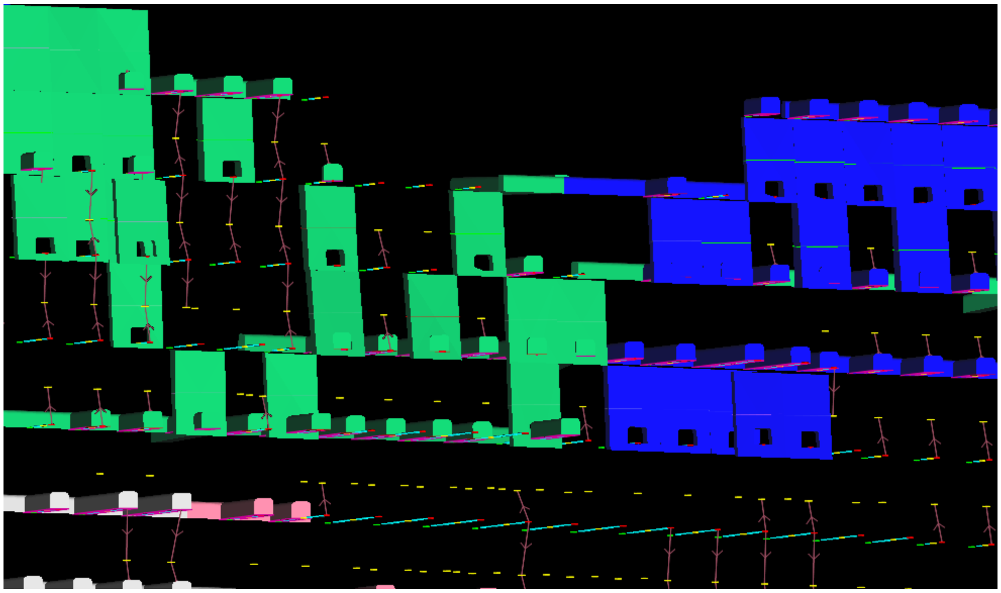


Figure 20: Stopes without Development

To address the lack of dependencies seen in Figure 20 and Figure 21, the solution can be found in two directions. The primary way to make a large set of dependencies is to create a rule, often a spatial rule, within the dependency creator. This rule should then link all tasks fitting the defining logic. The logic within a spatial rule is based on types of task, location of its centroid, and the position of surrounding tasks. In a setting such as the Kittilä Mine, where the LOM has four thousand stopes within the network, along with a comparatively large amount of development as well as intricate spatial dependencies, no single spatial rule was able to reach 100% accuracy between the desired dependency linkage and the resulting dependency linkage. This resulted in the creation of secondary rules to resolve the potential linkages left unconnected by the primary rule. At this point, it may become so that a secondary rule is broad enough that it begins to link tasks which are unrequired and therefore undesirable. The resolution is to find a balance and to visually inspect the network, layer by layer, visually checking the dependencies and correcting errors with the use of Deswik tools. As every stope centroid should be connected to or from at least six dependencies, there are a minimum of 24,000 dependency arrows to check for stopes alone. This does not include the resolution of any issues within the development linkages.

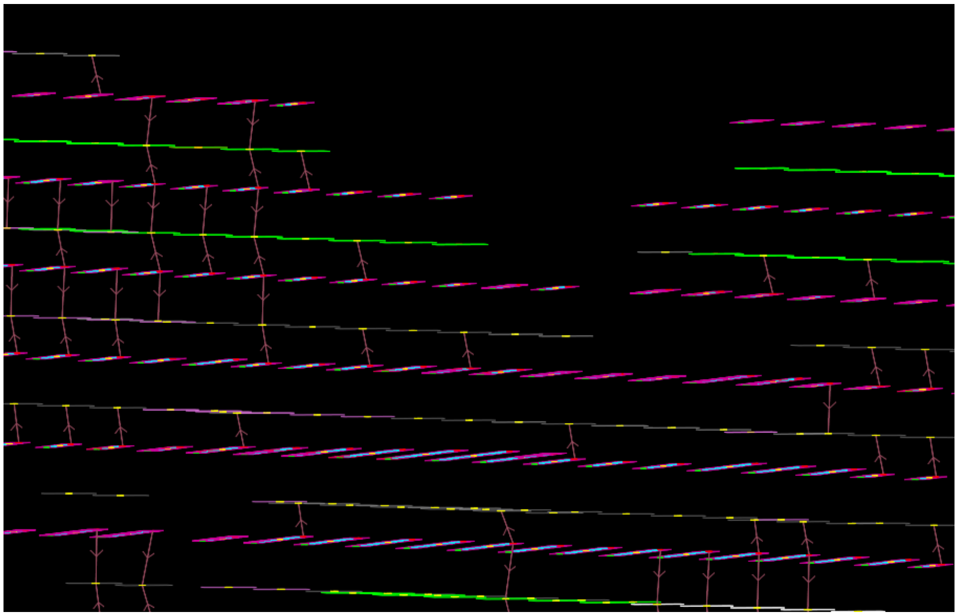


Figure 21: Drift- Stope Dependency map for Stopes without Development

The reason this issue was not clear before was because of the progression of development was logical prior to optimization. This is likely due to the panel priority directing development to the succeeding areas while production is preoccupied with the panel whose development was most recently finished. Because of this and the absence of pressure to create a significantly higher revenue given due to optimization, the developments and stopes appear in proper sequence.

Naturally, optimization is about finding the boundary between what is possible and impossible with the given constraints. The pressure created by optimization is one that will exploit any available systematic bug within the network to its benefit. This means that the network of dependencies must be entirely without holes. Every time a problem is resolved, the optimization will bring forward a new issue that it will be able to use to exploit the network until all holes in the network are patched. The difficulty of the fix is reflected again in the size and complexity of mine's network. Although, if a model can be perfected, not only with the dependencies resolved but also with remotely accurate costing, a best solution can be found.

6 Comments on Deswik

6.1 Advantages of Deswik

Deswik as a mine planning software has many opportunities to showcase its variety of technological and organizational advantages. The first of which may be its integration of the physical and scheduling networks. The detail of the breakdown of the physical model allows for a thorough foundational network for all future engineering and scheduling designs to be made. Alongside this physical network, the ability to establish required tasks and equipment for the completion of each physical piece, which is then integrated into the physical model, enables the user to manipulate the development of the mine and its scheduling simultaneously. This feature is one of the greatest benefits of Deswik. By applying an accurate and practical breakdown of tasks and resources to the progression of the physical model, the program allows for incredible flexibility during the mine planning process. Alterations of the mine plan may be made within minutes by implementing necessary deadlines or arbitrarily shifting development and production sequences into a desired order. As these sequences are controlled, the scheduling and physical networks should shift seamlessly into a new mine plan, and while this may be possible with other programs, Deswik has the ability to instantly show these planning changes via a time-lapse of the mine model which allows for visual confirmation of the new plan.

Another advantageous aspect of Deswik would be the application of attributes to physical pieces of the mine model. As these attributes are applied, they allow for each physical piece to be filtered by attribute allowing endless combinations of filters for organizational and engineering purposes. More importantly, given dimensions, mineral grades, priority status or development needs can be applied and using the reporting process, further engineering and financial calculations may be quickly applied and assessed. Additionally, the reporting process allows for quick filtering and organization of all sorts of financial and engineering data.

6.2 Disadvantages of Deswik

Through all of the amenities that Deswik offers, inconveniences can arise. Primarily the application of the real world operational breakdown within the mine to the task network can be challenging. In the creation of a small underground or surface mine, equipment and task needs may be relatively simple, for example the basic rhythm of drill, blast, muck may suffice through the majority of a surface mine plan. This flow is easy to model within Deswik due to the nature of each crew completing a large task in a bulk fashion, with extraneous operations rarely influencing these primary tasks. Oppositely, the equipment schedule of a large underground stope mine such as Kittilä, may be notoriously scattered. This, along with long and short term contractors shifting equipment in and out of the mine creates a situation where production values become increasingly complicated to model. Task and equipment variety is also increased, and with limited space within the mining drifts, task timing and equipment spacing required special attention to keep crews and equipment from crowding underground tunnels. It should be noted that Deswik has a solution for each of these issues within the program and while fixing a single problem may be easily handled, fixing multiple overlapping issues over a long term plan will quickly become increasingly difficult to model.

Another concern that was encountered involved the progression within the physical network. Generally speaking, large and technical task networks can become difficult to correct. During the creation of spatial rules to link sections of drifts so that the task network shows a logical progression (i.e. each physical piece must be mined after the preceding adjacent piece,) linking errors occurred a small percentage of the time. During trials of different linking rules, no single rule would work for all drifts across the mine. Creating a second rule often increased efficiency of linking drifts but also created various extraneous links which required deleting. After many trials, errors remained and required manual solutions. Under different circumstances this may have been fixed without much strain, however with the increased size of the underground network used in the project the amount of time required to solve all broken links was outside the scope of this thesis.

7 Conclusion and Recommendations

7.1 Conclusion

The study conducted a detailed assessment of the sulfur grades taken at various stages in the reconciliation process. These estimates were compared to the data found in mucking samples and the value of each source was determined. Prediction data from the Primary Block Model was shown to be the most practical source of sulfur prediction data. Block Model sulfur predictions are underestimated 60% of the time at an average value of 0.11% sulfur. This is hypothesized to be in part due to the estimation having a clear lower limit in combination with pockets of high sulfur throughout the deposit, skewing the deposit estimation via the nugget effect during the primary exploration drilling.

Various alterations to the LOM schedule and its settings were tested and no alterative schedules were able to improve upon the current LOM schedule in use. Even once the concise mining decisions made in the LOM by the planning team were removed and a new control was made, new issues arose. It was discovered that the complexity of development allocation within the Kittilä mine is beyond the compatibility of the Blend tool.

Most substantially, the use of optimization was found to bring any error within the network to the forefront of the schedule, as these gaps in dependencies are used by the tool as a shortcut to production and therefore revenue. Under the significant strain to improve the revenue in the mine or under essentially any rigorous enough production constraints, the optimization will search for a resolution and implement any mining sequence possible to create numerically acceptable results. This means that for optimization to work, the dependency network must be entirely valid and invulnerable in this way.

7.2 Recommendations

Though the mine has an acceptable schedule for production, some improvements to the process can be made in the future regarding the sulfur grades and the ore's stockpiling. Because of the error in misprediction, plan for all sulfur grades to be reported 0.11% higher than prediction. With conservative planning, the load on the autoclave system will be lightened.

The sulfur input to the mill should always contain the ore with the highest sulfur grade on hand, mixed with whatever material is suitable to be fed without overloading the system. Oppositely, very low sulfur ore should be isolated and stored for times where the need for sulfur dilution is high.

Recommended practice for the stockpiling of ore is for underground production to stay at least 48-72 hours ahead of the mill to allow for stope or mucking samples to be returned so that ore grades are able to be connected to the material for use in mill feed planning. Ore should be organized in piles by its predicted sulfur grade. Three or four stockpiles will allow for high, medium and low sulfur or possibly two moderate sulfur piles, one predicted to be above the threshold and one below. If space allows, more piles will increase access and efficiency.

The Deswik Schedule Optimization Tool may improve the NPV of the schedule, however applying the program would require a full rebuild of the mine model and may cause major disruptions to future development plans in order to improve NPV.

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